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Hydrologic Basis for Suspended Sediment Criteria

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Water quality criteria typically specify concentrations in the water column that will protect aquatic life from adverse effects. While this approach is applicable to suspended sediment concentrations in the water column, it may not be sufficient, for two reasons. First, a water column concentration for solids would provide protection from possible adverse physical effects on the biota, but would not necessarily protect against possible chemical effects due to toxics sorbed to the solids particles. Second, a water column criterion ignores possible effects (smothering of habitat, and chemical effects due to sorbed toxics) if the suspended matter settles from the water column. The question of sediment criteria is now under review by the Criteria and Standards Division (OWRS). The question of adverse effects due to toxics sorbed to suspended solids is complex, and should be considered in the development of criteria for suspended matter.

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HYDROLOGIC BASIS FOR SUSPENDED SEDIMENT CRITERIA

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EXECUTIVE SUMMARY

- The objective of this report is to discuss factors that are important to the development of criteria for suspended matter in the water column. Since the interest is in criteria for suspended matter in general, regardless of origin, no distinction is made between wastewater solids, commonly referred to as 'suspended solids,' and suspended matter of other origin, such as erosion or channel scour, which is often referred to as 'suspended sediment.'

- The term 'criteria' is used in this report in the context of the protection of aquatic life. The protection of other uses--such as contact recreation, navigation, water supply, etc.--is beyond the scope of the study.

- Several factors that are important to the development of a water quality criterion for suspended solids/turbidity are examined in this report. These factors include regional, physiographic, and seasonal considerations, and related hydrologic phenomena. Particular emphasis is placed, in Chapter 4, on statistical hydrology (frequency-intensity relationships) and on the combination of hydrologic information with biological information as a means of formulating criteria.

- Most suspended solids in a river can be attributed to nonpoint sources. Some nonpoint source suspended sediment is natural in origin and is nearly impossible to control. Most nonpoint source solids result from man's alteration of the environment--e.g., agriculture, mining, and urbanization. Although most cultural sources could be controlled, political and economic considerations render effective control problematic. The relative contribution of natural and anthropogenic sources of suspended sediment may shift in favor of the former during high flow periods when sediment in the water column due to natural erosion and channel scour may be high.

- The natural solids loading to a waterbody will vary from site to site, depending upon physiographic factors (slope, soil type, type of ground cover, etc.) and upon rainfall and runoff. Anthropogenic nonpoint source loadings will also vary strongly with the rainfall and runoff characteristics of a particular area. Point source loadings may be proportionately large during dry weather periods, although the concomitant low flows and low velocities may mean that suspended solids will settle rapidly and be cleared from the water column. During wet weather periods, point source loadings may remain constant, yet become insignificant compared to nonpoint source loadings added to the system. Given these considerations, it is apparent that seasonal and regional criteria are indicated that take into account the significance of natural and cultural nonpoint source loadings.

- Water quality criteria typically specify concentrations in the water column that will protect aquatic life from adverse effects. While this approach is applicable to suspended sediment concentrations in the water column, it may not be sufficient, for two reasons. First, a water column concentration for solids would provide protection from possible adverse physical effects on the biota, but would not necessarily protect against possible chemical effects due to toxics sorbed to the solids particles. Second, a water column criterion ignores possible effects (smothering of habitat, and chemical effects due to sorbed toxics) if the suspended matter settles from the water column. The question of sediment criteria is now under review by the Criteria and Standards Division (OWRS). The question of adverse effects due to toxics sorbed to suspended solids is complex, and should be considered in the development of criteria for suspended matter.

- Hydrologic events are particularly important to the generation of suspended sediment in a water body. The historical record may be analyzed to characterize seasonal suspended sediment concentrations in a water body.

- Comparatively little quantitative information is available that is descriptive of the effects of sediment on the biology of a water body. Even less is known about the effects of suspended sediment. The available data might suffice for initial investigations into the development of criteria, but a much more extensive data base eventually will be required in order to develop criteria that are as refined as those for some toxic chemicals, and that take into consideration the collective biota of a stream, and the different life stages of that biota.

- The effects of sustained exposure to suspended sediment may be of greater concern to adult forms than exposure to short pulses of suspended matter. This may not be true of other stages of the life cycle. Storm related pulses of suspended matter may be of little consequence to the biota. However, such pulses may resuspend sediment and carry it downstream until velocities subside and the solids settle out. Such resettlement may have adverse consequences for the biota.

- A procedure is discussed in Chapter 4 whereby the analysis of hydrologic phenomena and biological effects may be combined to frame criteria protective of aquatic life. This is a non-specific discussion, however, and only sets out a framework for the joint consideration of regional, seasonal, and biological factors.

- Equally as important as the specification of criteria for suspended solids is the establishment of a protocol for the enforcement of such criteria. In many cases the load and concentration attributable to a point source of suspended solids will be small compared to background levels. Background levels will certainly have to be taken into consideration and in many cases may render criteria meaningless. For those cases where background levels do not dominate, criteria might be appropriate.

1.0 INTRODUCTION

The purpose of this report is to investigate hydrologic/sediment load relationships that might be used to establish a water quality criterion for suspended sediment. The approach to development of criteria for suspended sediment is somewhat different from that for toxic chemicals because toxics concentrations will be low during high flow periods, while sediment concentrations will be high.

Suspended sediment in a stream is derived from point source discharges, nonpoint sources, and the resuspension of bottom deposits. High flows may scour the channel and resuspend a considerable amount of material. During dry weather periods, the volume of sediment entering a river system is reduced, velocities decrease, and suspended matter settles out.

Erosion and sediment transport are natural processes resulting from the interaction of many physical variables that can be described by, but are not limited to, the travel of water on the surface of the earth. The degree of erosion is a function of (1) the frequency, intensity, and distribution of precipitation; (2) the chemical and physical properties of the soil; (3) soil cover; and (4) the topography of the area, which both influences and is influenced by the erosion process.

Natural rates of soil loss depend on the characteristics of a particular region. A severe disruption in events may have a significant impact on the environment. The disruption can be caused by natural phenomena such as infrequent but severe storm events or by such activities as rapid urbanization or widespread clearing for agricultural purposes. The influence of man on sediment loadings may be seen in cropland erosion, mining, construction, and other activities.

The specific effects of sediment on aquatic organisms depend on sediment characteristics and concentrations. Material that is suspended in the water column decreases light penetration and may affect photosynthesis and primary production. Suspended sediment also acts directly on some aquatic life, through abrasion, by clogging gills, and by inhibiting feeding activity. Settled sediment may modify and render habitats unsuitable for certain organisms. If large amounts of sediment settle, the habitat and its resident biota may be smothered.

The variability of factors influencing suspended sediment necessitates the development of criteria on a regional and perhaps seasonal basis. The hypothesis to be examined in this report is that a comparison of regional and seasonal variations in aquatic life cycles to regional and seasonal variations in hydrology and suspended sediment loads offers a promising approach to the development of suspended sediment criteria and standards.

The following sections of this report outline a possible basis for establishing criteria. Chapter 2 presents a discussion of the factors influencing suspended sediment loads and the mechanics of sediment transport; a review of previous studies on observed spatial and temporal variations of sediment concentrations; a review of various methods for predicting and analyzing sediment loads; and a discussion of the impacts of urbanization on sediment concentrations.

Chapter 3 discusses the impacts of suspended sediment on aquatic life. Aquatic life is discussed by category: primary producers and zooplankton, macroinvertebrates, salmonid fish, and other fish. Categories are based on similarity of species and, in particular, reproductive and life cycle stages. Attempts are made to relate life cycle stages and respective tolerances of aquatic life category to sediment concentrations under seasonal and regional patterns.

In Chapter 4, several aspects of hydrologic regions and seasons are discussed, and an approach is proposed by which hydrologic data and toxicity data may be considered jointly in order to develop criteria. In this joint approach, the treatment of hydrologic data is based on an analysis of the number of events of a given intensity and duration rather than the customary type of analysis that is based on the cumulative duration of a given flow rate.

2.0 SEDIMENTATION PROCESSES

2.1 GEOMORPHOLOGY

Geomorphology is the study of the configuration and evolution of landforms. Hydrogeomorphology is the science of landform evolution as governed by the hydrologic cycle. The interaction between geomorphology and the hydrologic cycle is significant, for the topographic structure of the earth's surface not only affects the motion and storage of water after a rainfall, but in turn is affected by it.

In the hydrologic cycle, overland flow occurs when the rate or quantity of rainfall exceeds the amount of precipitation that can be intercepted by vegetation, or that is lost to infiltration and evaporation. Surface flow occurs due to energy gradients causing a conversion of potential to kinetic energy. When the surface flow velocity exceeds a critical value, erosion of the local surface material occurs.

The extent of erosion and the topographic characteristics of the land are related to the climate and the geology of the region. The permeability and strength of surface materials are characteristic of the geology; the intensity, duration, and distribution of precipitation are characteristics of the climate and meteorology; and the geology and meteorology combined determine the dynamic relationships between vegetation, roughness, and surface slope.

Geomorphology involves dynamic activities in which the land surface is in a slow but continuous state of change. The thermodynamic approach is to envision the drainage basin as striving toward a state of compromise between a uniform distribution of energy expenditure and a minimum total rate of work. The degree of erosion, sediment transport, and sediment deposition reflects the dynamic state.

2.2 SEDIMENT TRANSPORT MECHANICS

Sedimentation involves the processes of erosion, entrainment, transport, deposition, compaction, and cementation of sediment particles. The removal of soil particles from their environment is called erosion. Erosion occurs when shear forces caused by flowing air or water, or by the impact of rainfall, are greater than the gravitational and/or cohesive forces which hold soil particles in place. Entrainment is the process in which eroded soil particles become part of the flow. Transport is the conveyance of sediment particles within the flow regime. The nature of movement and concentration of suspended sediment depends on the size, shape, and specific gravity of the sediment particles in relation to the turbulence and velocity distribution in the channel. Sediment will remain in suspension until gravitational forces exceed uplift from vertical components of velocity in the water discharge, at which point deposition of particles onto the land surface or channel bed will occur. Compaction results from the weight of successive layers of deposited sediment.

The reader is referred to Sedimentation Engineering (ASCE, 1975) for a comprehensive discussion on sedimentation including the theory of particle characteristics and behavior.

2.3 METHODS OF PREDICTION AND ANALYSIS

Many formulas have evolved over the past 50 years to predict sediment behavior, concentration, and yield. Most theories address individual aspects of sedimentation such as bed load movement theory or suspended sediment distribution in a given channel cross-section. Other relationships link sediment load with hydraulic relationships. Unfortunately, many of these are predictive equations or annual estimates and were developed for engineering purposes such as estimating reservoir siltation and channel morphology as opposed to estimating concentrations in suspension. Examples of models for sediment processes are illustrated in Table 2-1.

Methods of predicting sheet erosion on overland areas can be estimated using the Universal Soil Loss Equation and adaptations of the Musgrove Equation (ASCE, 1975). The Universal Soil Loss Equation computes the average annual soil loss (tons per acre) from a specific field based on soil erodibility, rainfall, topographic, crop management, and conservation practice factors. The Musgrove Equation computes average top soil loss in tons per acre based on an erodibility factor for the soil, soil cover factor, land slope, slope length, and the 30-minute, 2-year frequency

Table 2-1. Sediment Process Models
(Source: USGS 1982)

Process	Empirical/component method	Conceptual simulation	Statistical		
			Regression/correlation	Probabilistic	Stochastic
Erosion	Horton, sheet-erosion equation. ARS, universal soil-loss equation. Musgrave, soil-loss equation. Ellison, soil-splash equation. Dragoun, sheet-erosion equation.	Negev, sediment-erosion-transport model. ARS upland erosion model. Hydrocomp, simulation programing.	Anderson, sediment-yield equation. Fleming, suspended-load design curves. SCS, gully erosion equation. Beer and Johnson, gully growth equation. Thompson, gully advance equation.	Frequency analysis of sediment-yield transport and deposition.	
Transport	Schulits, computer programs for bedload formulas. Du Boys, transport formula. Einstein, bedload function. Colby, modified Einstein method. Blench, regime equation. Laursen, transport theory. Inglis-Lacey, transport formula. Toffaleti, transport formula.		Sediment-rating curves.		Random generation of sediment data. Sakhan, Riley, and Renard, simulation of sediment transport with stochastic transfer at the streambed.
Deposition	Fall velocity theory. Sediment suspension/deposition theory. Density current theory. Ackerman and Corinth, reservoir sedimentation equation.	Thomas, U.S. Army Corps of Engineers reservoir sedimentation model. (Also simulates transport.)	Farnham, Beer, and Heinemann, regression analysis of reservoir sedimentation. Stall and Bartelli, correlation of reservoir sedimentation and watershed factors.	Einstein, bedload function.	

rainfall. These relationships are limited in the areal extent used for application.

Many formulas have been developed to determine the discharge of bed sediment under steady uniform flow. Sedimentation Engineering (ASCE, 1975) presents a number of these formulas, including:

DuBoys, 1879
Meyer-Peter, 1948
Schoklitsch, 1935
Shields, 1936
Meyer-Peter and Muller, 1948
Einstein-Brown, 1950
Einstein Bed Load Function, 1950
Laursen, 1958
Blench Regime Formula, 1966
Colby, 1964
Engelund-Hansen, 1967
Inglis-Lacey, 1968
Toffaleti, 1969

The formulas are based on various governing relationships and incorporate several flow and sediment characteristics including depth of flow; mean velocity; bed slope; shear stress; friction factors; particle size, distribution, and specific weight; and fluid temperature. The accuracy of prediction is dependent upon the ability to properly identify the governing parameters. Figure 2-1 shows a comparison between several bed sediment prediction formulas and observed sediment discharge as a function of water discharge for the Colorado River. It can be seen that the ability to match observed data varies considerably between formulas.

The estimation of sediment discharge above the bed is generally based on sediment and flow observations at gaging stations. The U.S. Geological Survey (USGS) determines suspended sediment concentrations for many water quality stations throughout the country from samples collected using depth integrated samplers. Mean concentrations in the cross-sections are obtained by taking samples at several vertical locations or by applying a coefficient to a single sample (Guy, 1970; Porterfield, 1972). For periods when no samples are taken, estimates of daily suspended sediment loads are based on water discharge or sediment concentrations immediately prior to or after

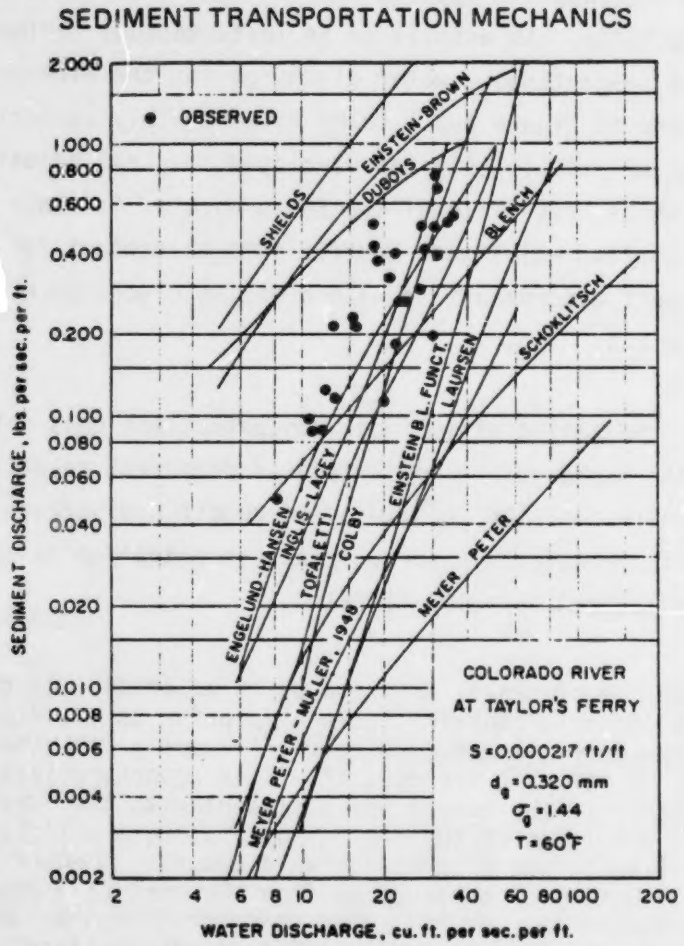

Figure 2-1. Comparison of Bed Transport Formulae

(Source: ASCE, 1975)

the period. Records of particle size distribution of the suspended sediment and bed material are also kept by the USGS.

The relationship between sediment discharge rate and flow at a cross-section may be depicted in a sediment rating curve. Colby (1956) developed sediment rating curves for six gaging stations in the United States in order to study the possible applications of these curves to the estimation of sediment discharge. An example of an instantaneous sediment discharge plotted against instantaneous water discharge for the Niobrara River in Nebraska is shown in Figure 2-2. Colby noted monthly variations in the sediment-discharge relationship and developed seasonal adjustment factors, an example of which, for White River, South Dakota, is shown in Figure 2-3. An example of similar adjustment coefficients to account for variations in suspended sediment concentrations with a rising discharge hydrograph is shown in Figure 2-4.

Unfortunately, the timing of sediment concentrations does not always correspond with discharge. A comparison of different relationships of sediment concentration with the timing of runoff hydrographs is shown in Figure 2-5. The relationship of sediment concentration to the hydrograph has been characterized by Colby (1956):

> If the distance of travel from the point of erosion is short or the stream channels contain little flow prior to the storm runoff, the peak concentration of fine material usually coincides with the peak flow, or somewhat precedes it. Peak concentrations of fine material early in the runoff is consistent with the idea that loose soil particles at the beginning of a storm will be eroded by the first direct runoff of appreciable amount. However, the flow from one tributary of a stream or from one part of a drainage area may be markedly lower or higher in concentration than the rest of the flow, and the time of arrival of such unrepresentative flow may determine the peak of fine-material concentration. The peak of the concentration of fine material may even lag far behind the peak of the flow, if the fine material originated far upstream and if, just before the storm runoff, the stream channel contained large volumes of water having low sediment concentrations.

Figures 2-6 and 2-7 illustrate the variation in suspended sediment concentration to water discharge for rising and falling hydrographs.

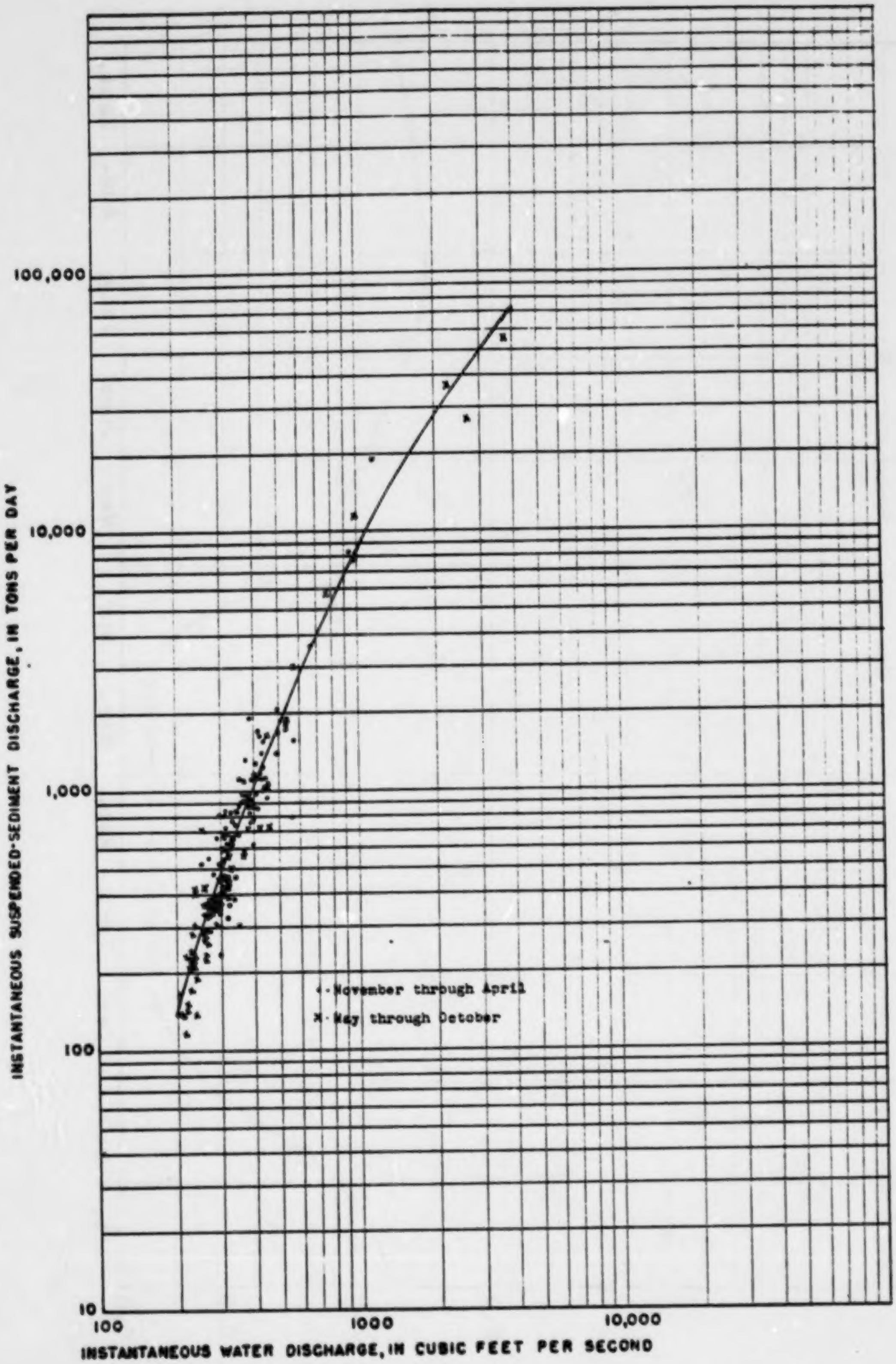

Figure 2-2.—Instantaneous Sediment Rating Curves for Niobrara River Near Cody, Nebraska. (Source: Colby, 1956)

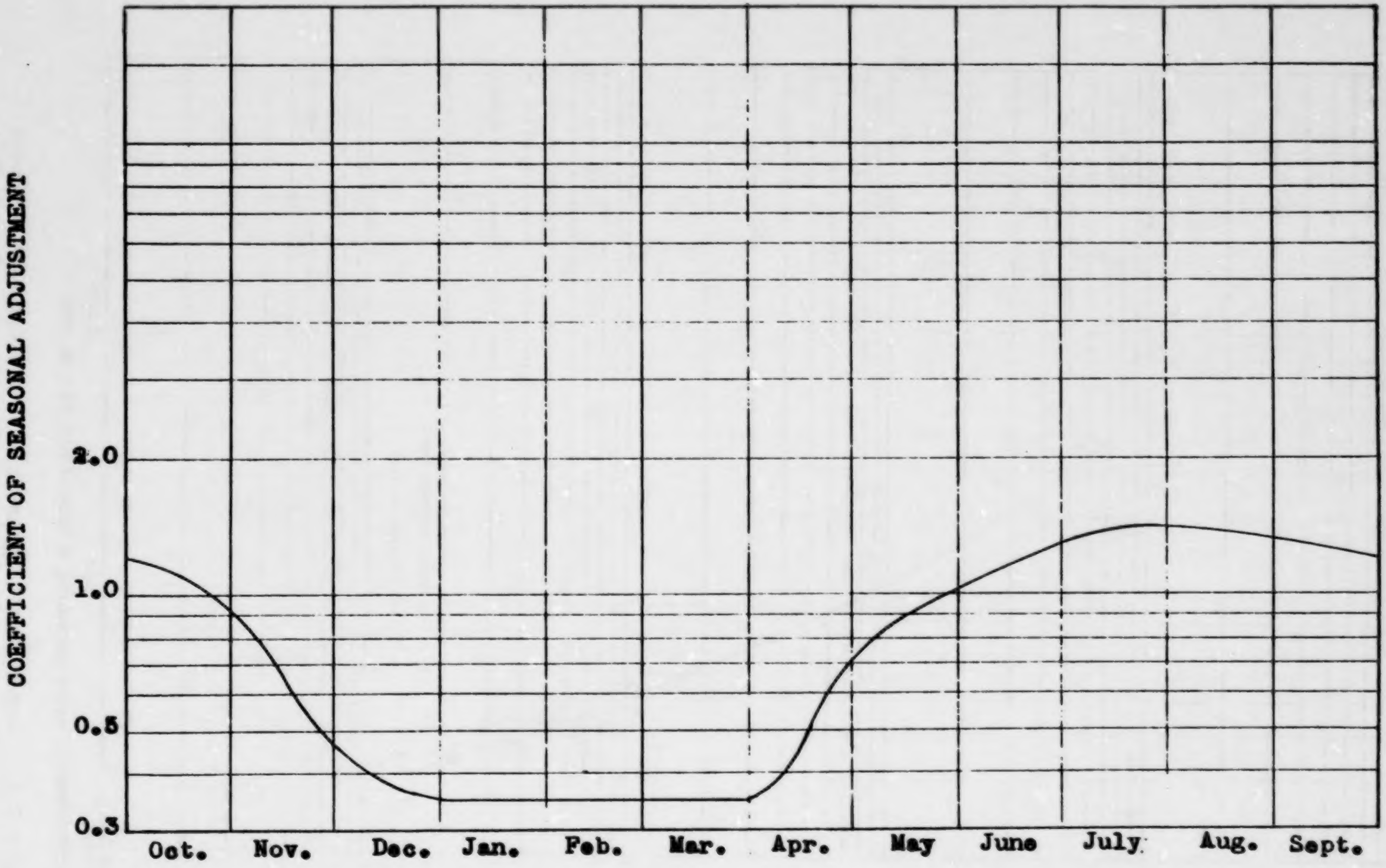

Figure 2-3. Seasonal Adjustment to Discharges of Sediment,in Clay and Silt Sizes, White River Near Kadoka, SD. (Source: Colby, 1956)

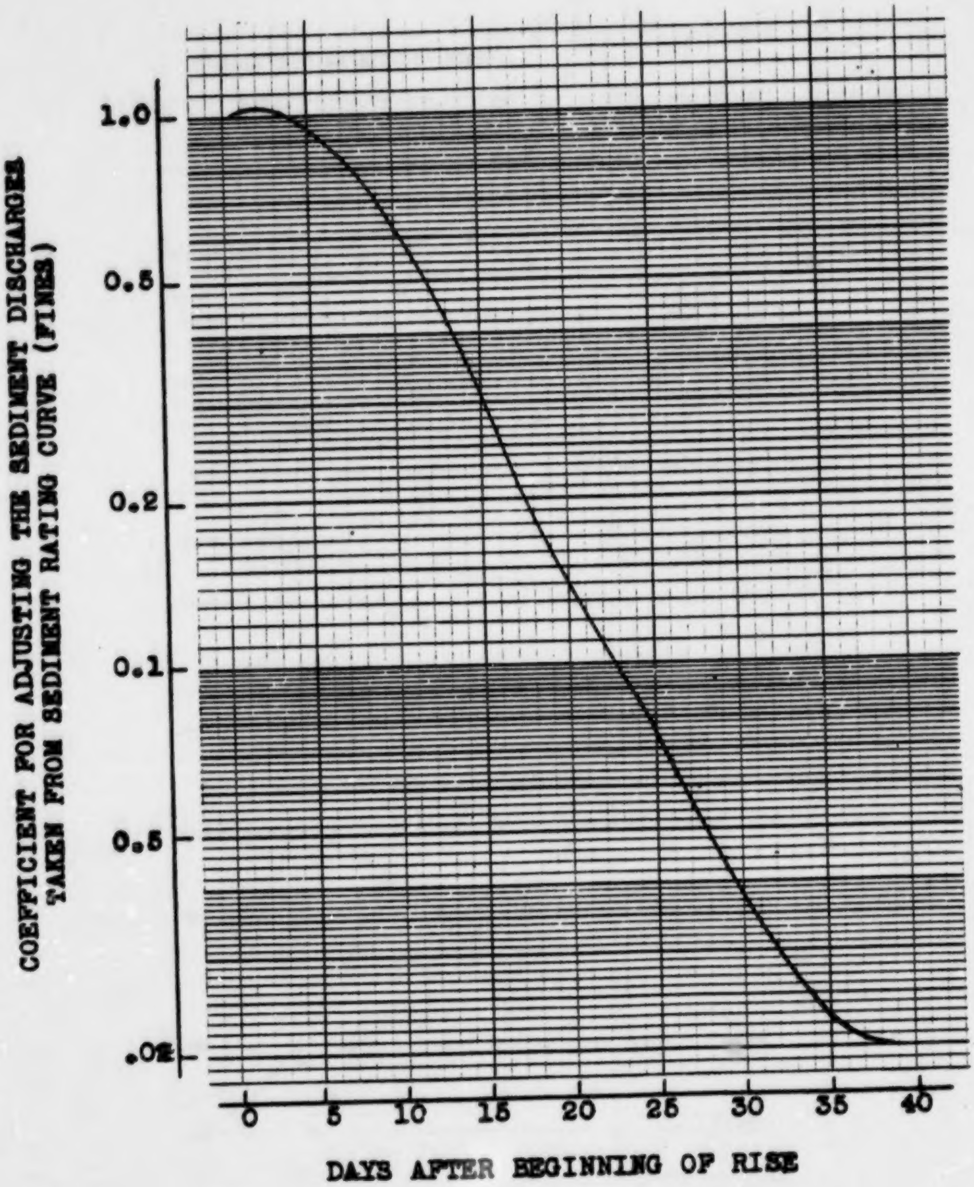

Figure 2-4. Approximate Average Variation of Coefficient of Sediment Discharge (fines) With Elapsed Time After Beginning of a Rise, White River Near Kadoka, SD. (Source: Colby, 1956)

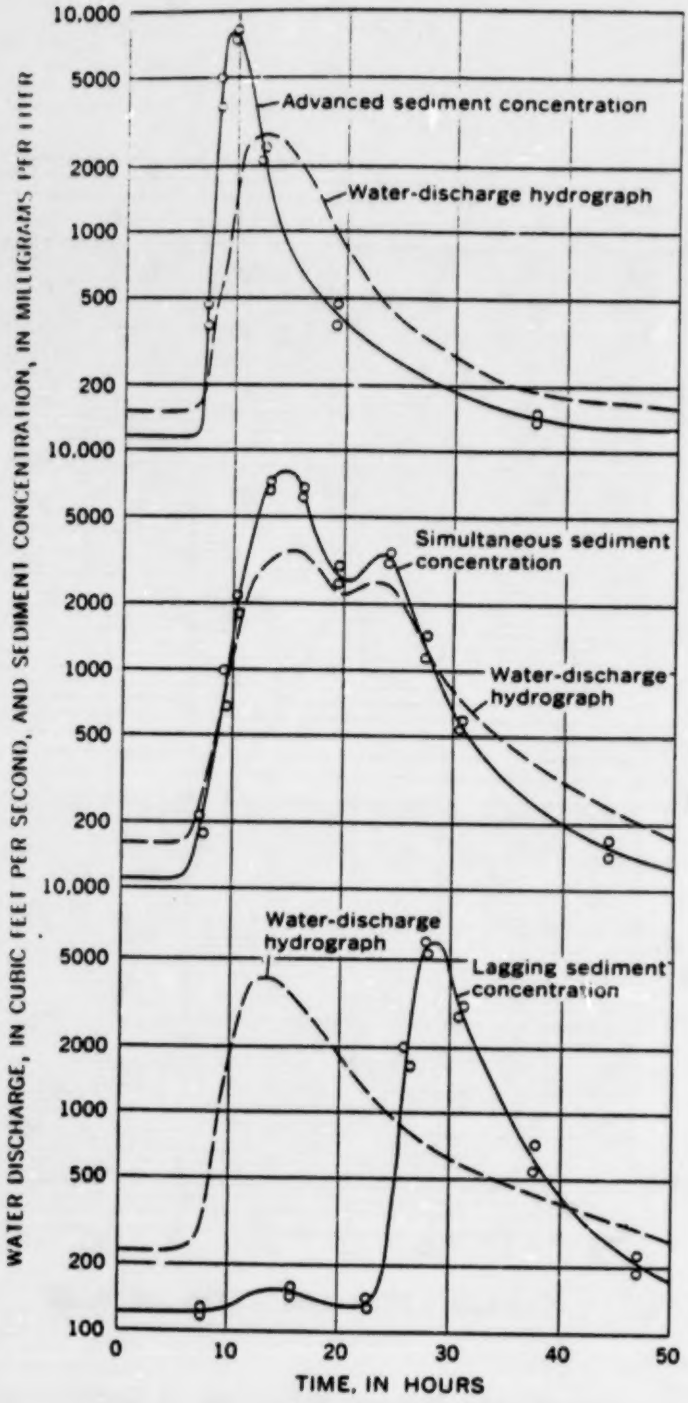

Figure 2-5. Comparison of Different Sediment Concentration Relationships With Timing of Runoff Hydrograph (Source: Guy, 1970)

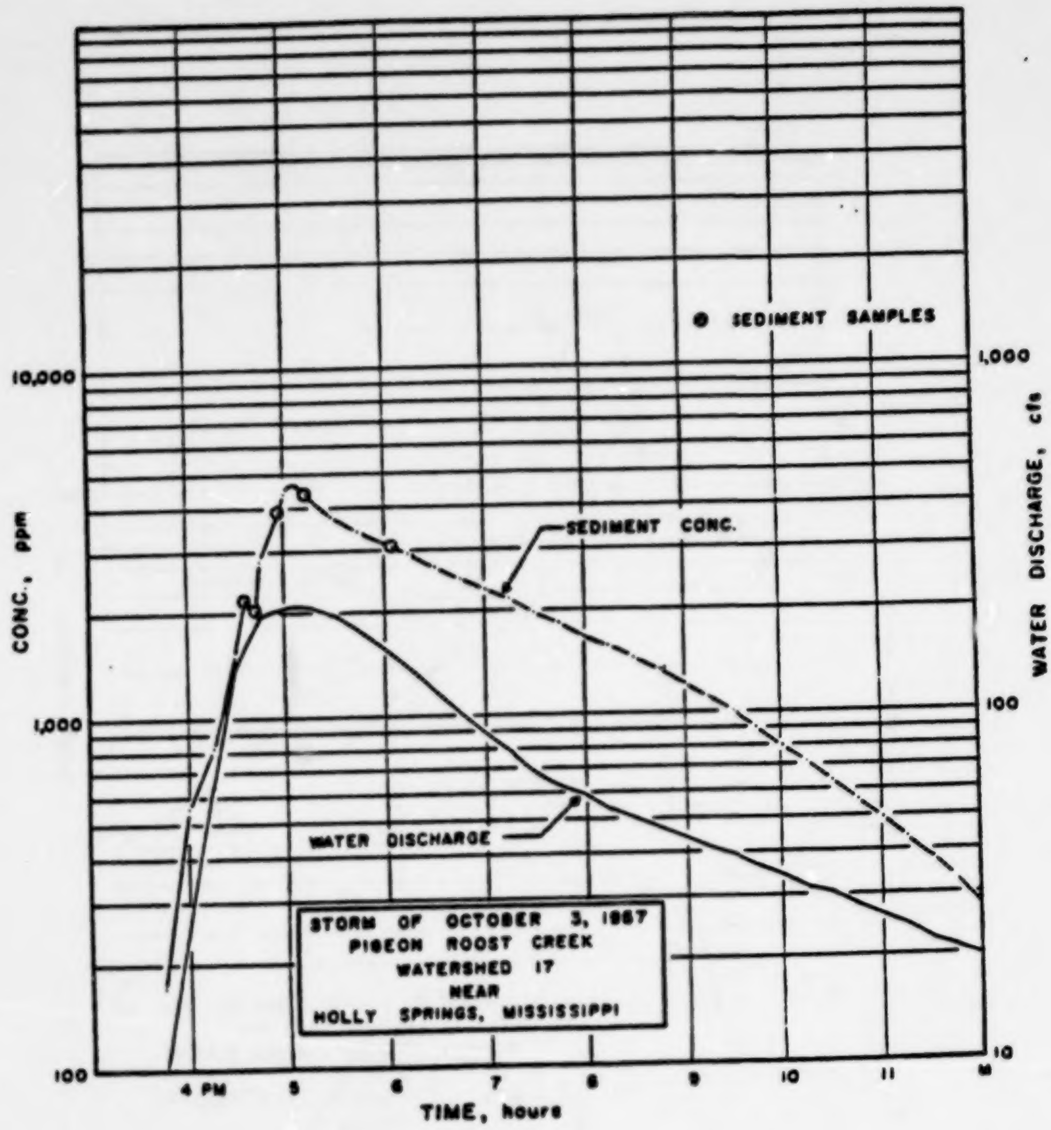

Figure 2-6. Variation in Suspended Sediment Concentration With Hydrograph for a Low Intensity Storm (Source: ASCE, 1975)

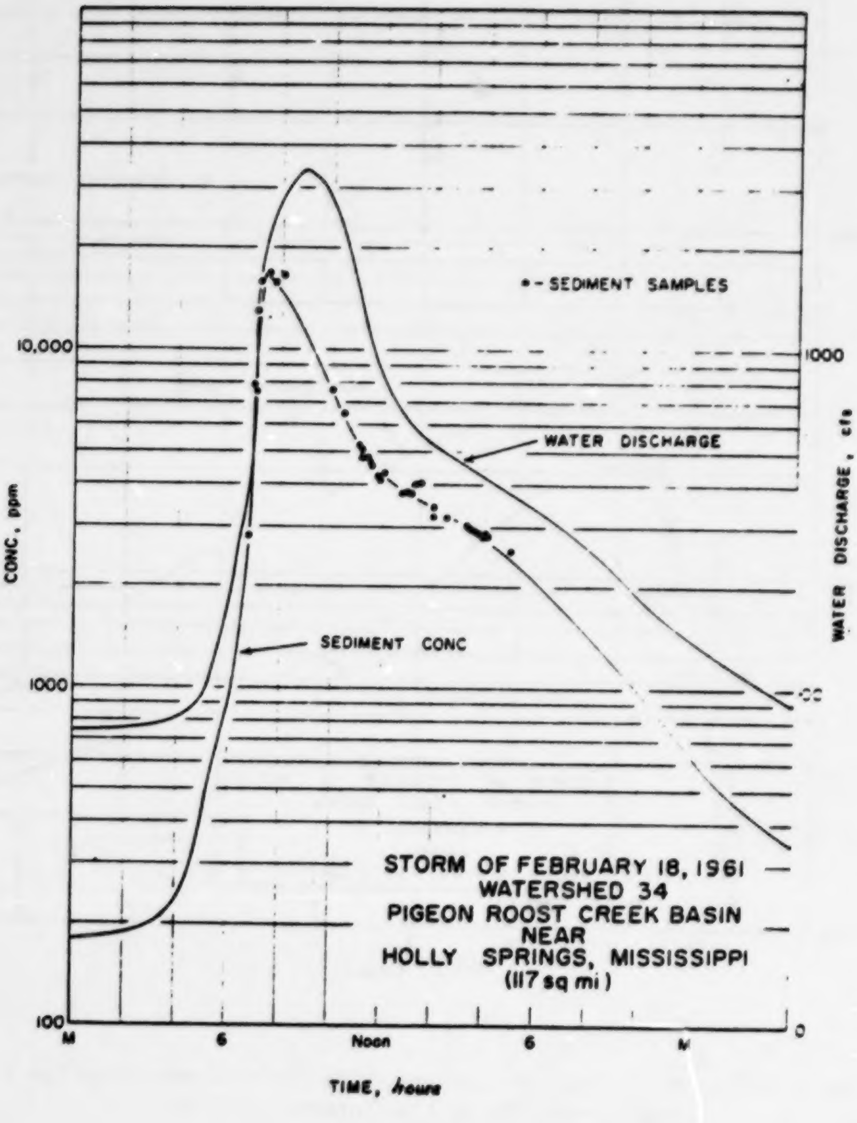

Figure 2-7. Variation in Suspended Sediment Concentration With Hydrograph for a High Intensity Storm (Source: ASCE, 1975)

Colston (Overton and Meadows, 1976) developed a regression model to predict instantaneous variations of suspended solids concentrations as a function of water discharge and time elapsed since the start of the storm. The correlation coefficient obtained from the regression was found to be 0.76. It is important to note that models developed by optimizing coefficients, unless otherwise tested, are specific to the area and to the ranges of data used in the optimization.

A sediment rating curve developed for the Powder River in Wyoming was developed by Langbein and Maddock (Linsley, et al., 1975) as shown in Figure 2-8.

Hadley and Schumm (1961) compared mean annual sediment accumulation with rock type and drainage density in a New Mexico-Arizona study area. Hadley and Schumm also correlated mean annual sediment accumulation to relief ratio in 26 basins in the Cheyenne River basin with good results. It was found, however, that relief ratio was not a good measure of erosion rates in basins with two distinct types of topography.

The U.S. Army Corps of Engineers Hydrologic Engineering Center has developed several computer programs written in FORTRAN to analyze processes of sedimentation. The first, entitled "Suspended Sediment Yield" (HEC, 1968), performs a complete suspended sediment transport study at a specific stream gaging station (USGS, 1968). The program has the capability of performing the following options:

1. The weighted average size distribution and the unit weight of suspended sediments can be computed.
2. If the user desires, the program will compute the relationship between the logarithms of instantaneous sediment loads and the logarithms of the corresponding flows. The resultant regression equation and correlation coefficients are also determined. Logarithmic relationships are used to compensate for non-linearity in the relationships between discharges and suspended sediment concentrations; regressions based on low versus high flow may differ.
3. Multiple correlations of the logarithms of mean daily sediment loads against the logarithms of mean daily flows and elapsed time from previous peak flows can be developed. The regression based on

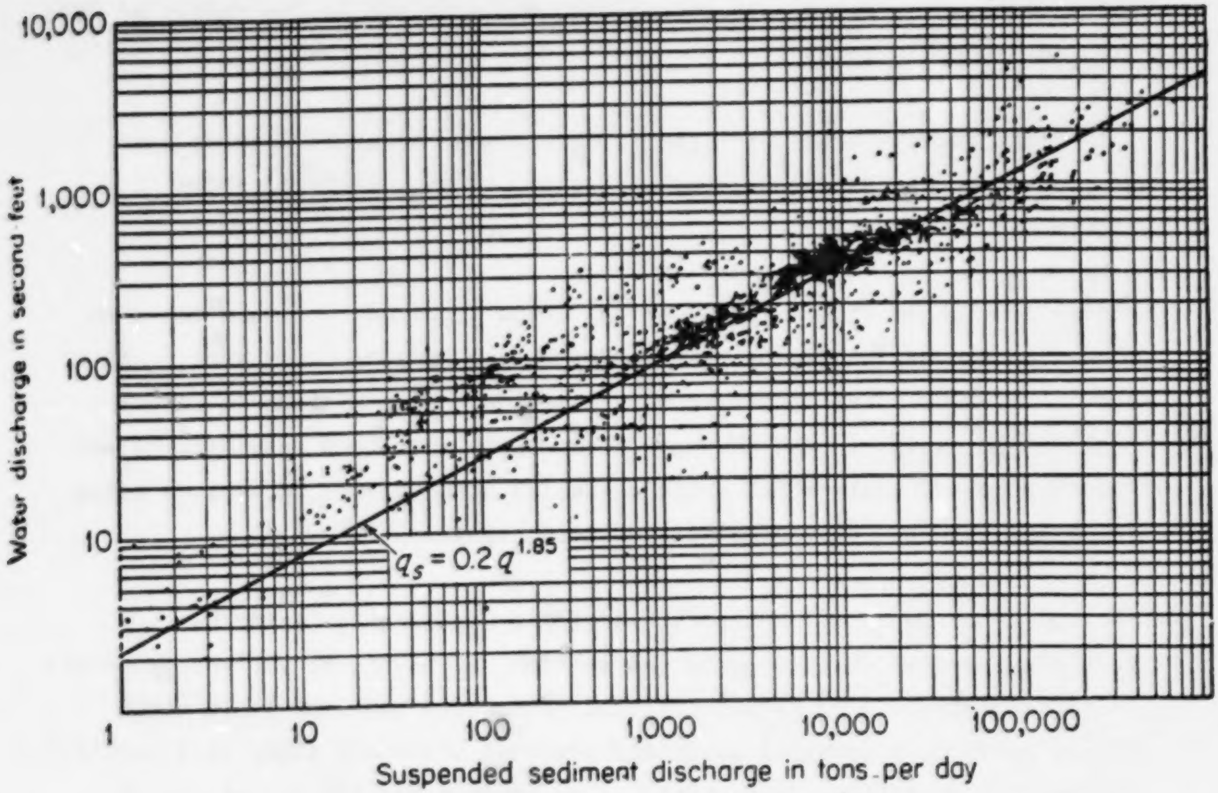

Figure 2-8. Sediment Rating Curve for the Powder River at Arvada, WY (Source: Linsley et al., 1975)

elapsed time from previous peak flow is introduced to compensate for temporally varying sediment load relations as caused by significant bank and channel erosion and landslides due to major floods. These conditions can cause temporary sediment concentrations of 10 to 20 times greater than expected concentrations.

4. The daily load equation (from part 3) can be applied to measured daily flows to estimate annual suspended sediment loads.

The program "Deposit of Suspended Sediment in Reservoirs" (HEC, 1967a) determines the distribution and location of sediments deposited in a reservoir, sediment inflow loads, the trap efficiency of the reservoir, and size distributions of passing sediments. Size ranges of sediment are routed through sections of the reservoir and deposition of sediment is computed as a function of sediment size, reservoir temperature, inflow variation, reservoir configuration, and mode of reservoir operation. An inflow-duration relationship is used to describe inflow variations of flow and sediment.

The program "Reservoir Delta Simulation" (HEC, 1967b) computes profiles for sediment deposits from bed load forming the delta at headwaters of the reservoir based on total bed load and reservoir cross-section.

The Stanford Sediment Model developed by Neger in 1967 ties suspended sediment production and transport processes with the runoff dynamics of the Stanford Watershed Model (Gregory and Walling, 1971). The determination of suspended sediment, divided into wash load and bedload components, is controlled by model parameters that must be estimated or established by optimization from observed data. Gregory and Walling point out that considerable improvements could be made to the model by including flood plain deposition and seasonal effects.

Onishi and Wise (1982) developed the Instream Sediment-Transport Model (SERATRA), an unsteady, two-dimensional finite element computer program to simulate sediment transport, dissolved contaminant transport, and particulate transport (contaminants adsorbed by sediment) based on advection, diffusion, and decay for each of three sediment size fractions. Required input includes geometric configuration; particle settling velocities, densities, and diameters; critical sheer stresses for sediment scouring and deposition; diffusion coefficients; contaminant degradation and decay parameters; and initial condition and inflow concentrations and discharges.

Other models have been developed to simulate erosion, transport, and deposition of suspended sediments in estuaries. One such model, SEDIMENT II (Ariathurai, et al., 1977) was developed under the Dredge Material Research Program of the U.S. Army Corps of Engineers between the U.S. Army Engineer Waterways Experiment Station and the University of California at Davis. SEDIMENT II is a two-dimensional finite element model which requires expressions for rates of erosion and deposition from previous experimental studies.

2.4 SPATIAL AND SEASONAL VARIATIONS

Soil cover is affected by climate, geology, and meteorology, all of which in turn are causative factors in seasonal and spatial variations in suspended sediment.

The amount of erosion can be related to climate or mean annual temperature and rainfall as shown in Figure 2-9. Erosion is minimal at temperatures below freezing, at rainfall and temperature conditions producing dense vegetation, and at temperatures high enough to yield low runoff due to evapotransporation. Maximum erosion occurs at temperatures and rainfall causing high runoff and/or poor vegetation cover.

In 1958 Langbein and Schumm (Gregory and Walling, 1971) related annual sediment yield to annual precipitation for basins on the order of 3,500 km^2 in the United States. The relationship shows that sediment yield is maximum for about 30 cm of annual precipitation and a mean annual temperature of 10°C, but is smaller for greater annual precipitation. The variation due to precipitation can be explained by the interaction of vegetation and rainfall with runoff and erosion. Langbein and Schumm developed similar relationships of mean annual sediment yield versus precipitation for other mean annual temperatures.

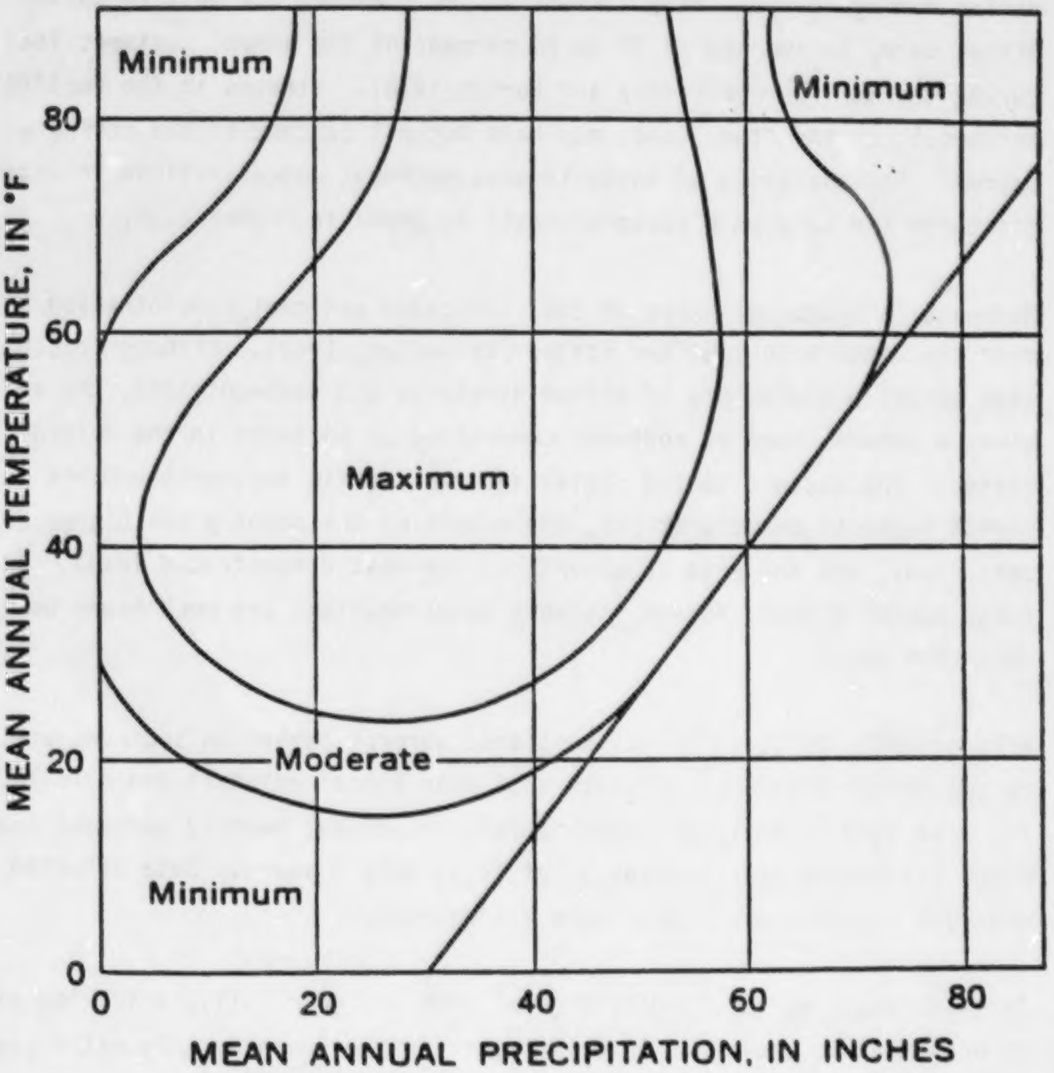

Figure 2-9. Relative Erosion as Related to Mean Annual Temperature and Precipitation (Source: Guy, 1970)

For many streams the greatest concentrations of suspended sediment occur during spring runoff. Many streams in the northern and eastern United States carry an average of 70 to 90 percent of the annual sediment load during the spring runoff (Guy and Norman 1970). Streams in the Pacific Northwest, on the other hand, may have highest concentrations during winter storms. Relationships of instantaneous sediment concentrations to water discharge can vary on a seasonal basis as shown in Figure 2-10.

Rainwater's Hydrology Atlas of 1962 indicated sediment concentration ranges over the conterminous United States (Rainwater, 1962). Although based upon mean annual measurements of stream discharge and sediment load, the atlas gives a general idea of sediment concentration patterns in the United States. The eastern United States and the Pacific Northwest exhibit the lowest sediment concentrations, the middle of the country has higher sediment loads, and the arid southwest has the most concentrated loads. It is quite apparent that average sediment concentrations are much lower below dams than above.

Wilson (1972, 1973, 1977) has published several papers on sediment yields in the United States as a function of mean annual rainfall and climate. The data used to analyze sediment yields represent monthly sediment and water discharges over periods of at least 3 to 5 years. Data affected by upstream regulation of flows were disregarded.

In these analyses the "sedihydrogram" (SHG - Figure 2-11), a log-log plot of mean monthly sediment yield (tons/mi^2) versus mean monthly water yield (tons/mi^2), was defined in order to illustrate sediment data on a seasonal basis. Seasonal variations in the sedihydrograms appeared to occur in two basic patterns. The first pattern (represented by the Eel River SHG in Figure 2-11) is typical for areas along the West Coast, which has a mediterranean climate regime. The mediterranean climate exhibits hot summers with little rainfall, and wet winters with a lot of rainfall.

The other two SHG's in Figure 2-11 are typical of a continental climate regime, which is found throughout the conterminous United States (except on the West Coast). A continental climate is typified by relatively wet

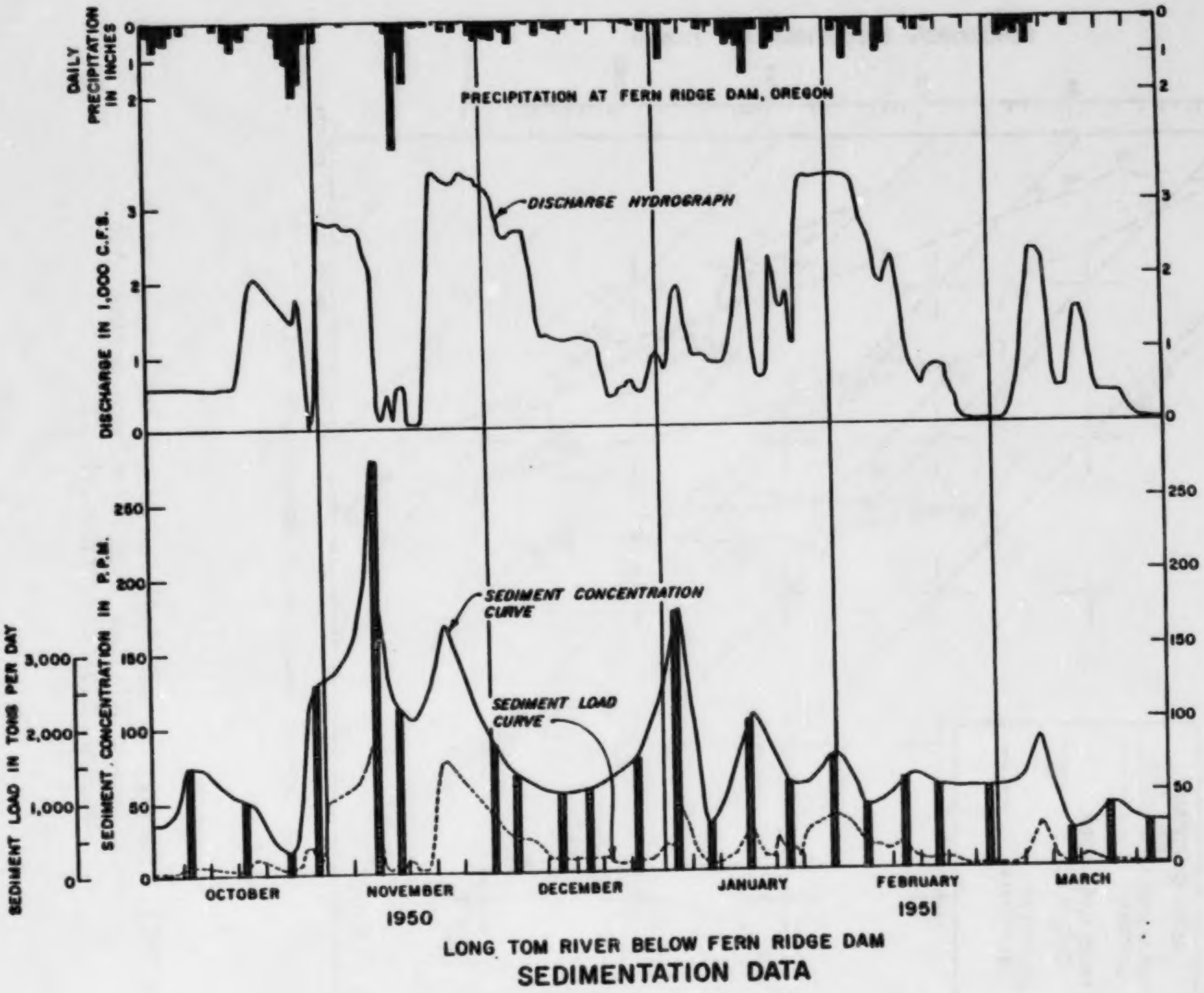

Figure 2-10. Seasonal Relationship Between Sediment Concentration, Sediment Load, Discharge, and Precipitation for Fern Ridge Dam, Oregon. (Source: Thomas, 1970)

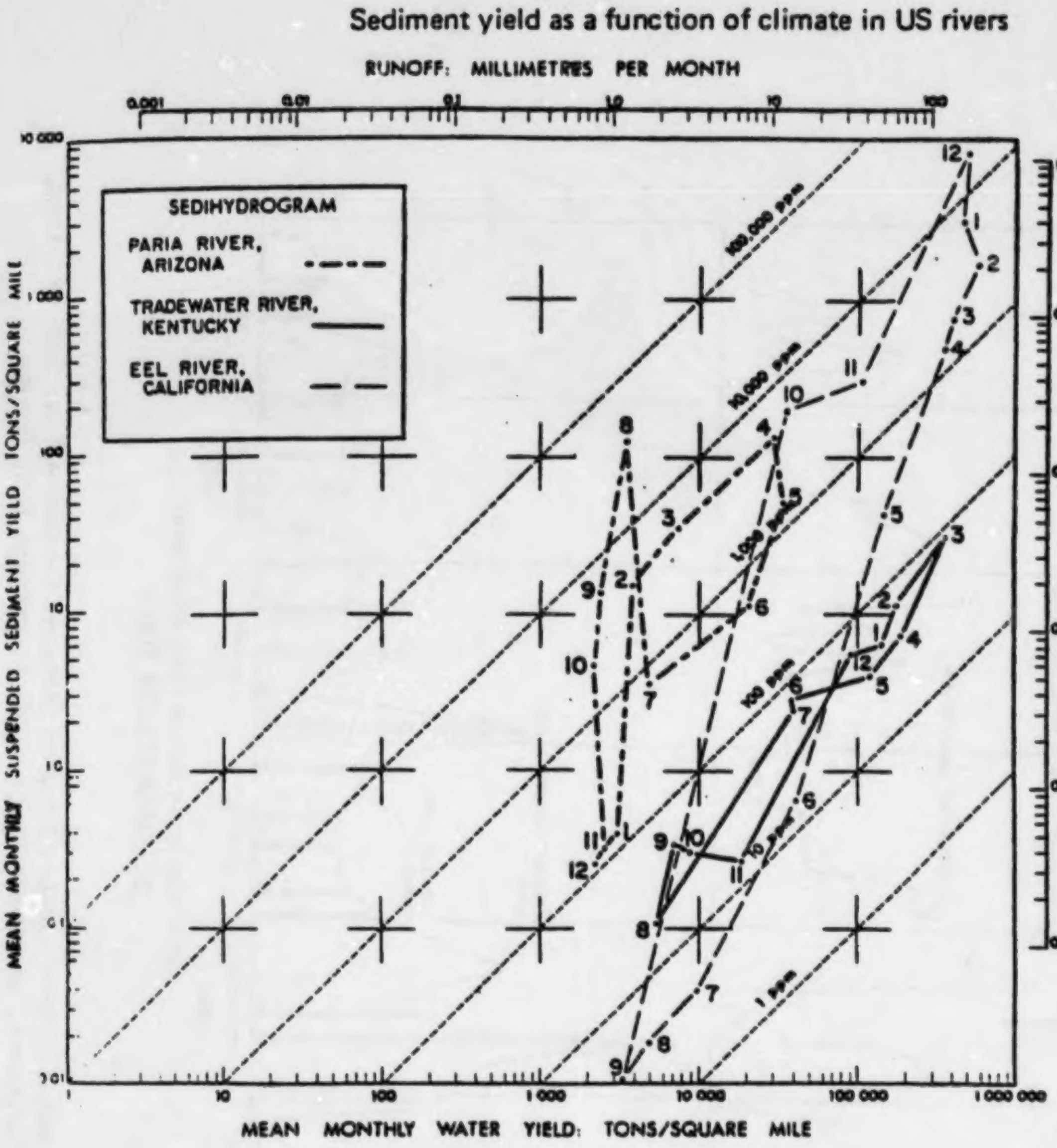

Figure 2-11. Sedihydrograms (SHG) for Rivers Influenced by Different Climates (numbers denote months, i.e., 1=January, Source: Wilson, 1977)

summers; often with short, intense thunderstorms. Winters are generally cold and dry in the west, mild and humid in the east.

In addition to climate, factors such as land use, lithology, soil type, and vegetation also affect sediment yields. In Figure 2-11, the Paria River in Arizona and the Tradewater River in Kentucky are both areas with a continental climate. The SHG's are different because the runoff from summer thunderstorms in the semi-arid west is not hindered by vegetation, and sediment is flushed into the streambeds. In the east, less runoff is carried into streams during short storm events, so a corresponding sediment increase is not observed.

Figure 2-12 illustrates the effect of land use on the SHG for two sites in Maryland. The agricultural site (Monocacy River) is fairly well vegetated and hence the summer sediment peak is not so pronounced. In the nearby urban area (Anacostia River), the summer sediment discharge peak is higher than that of winter.

Wilson (1977) presents an unrefined model which relates types of air mass to water yield and sediment concentration, and ultimately to sediment yield (Figure 2-13). Table 2-2 sums up the relationships in Figure 2-13. The air mass abbreviations in Table 2-2 stand for:

mT - maritime tropical, dominant summer air mass in east

cP - continental polar, dominant winter air mass over north-central portions of the country

mPa - eastern U.S. in winter; mixture of mT and cP

mPb - central U.S. in summer; mixture of mT and cP

mPc - maritime polar, dominant air mass of Pacific Coast in winter

cTu - western U.S. in summer (except coast)

mTs - Pacific coast in summer.

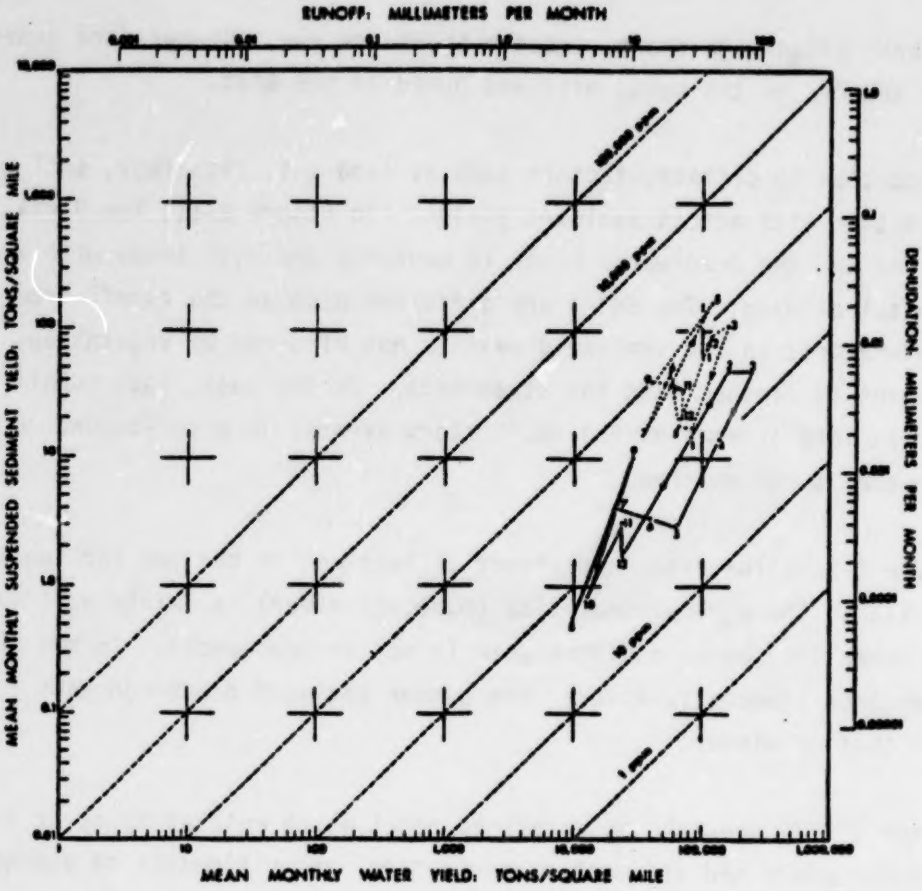

Figure 2-12. Effect of Land Use on SHG for Two Sites in Maryland (dashed line is for Anacostia River, solid line is for Monocacy River). (Source: Wilson, 1972)

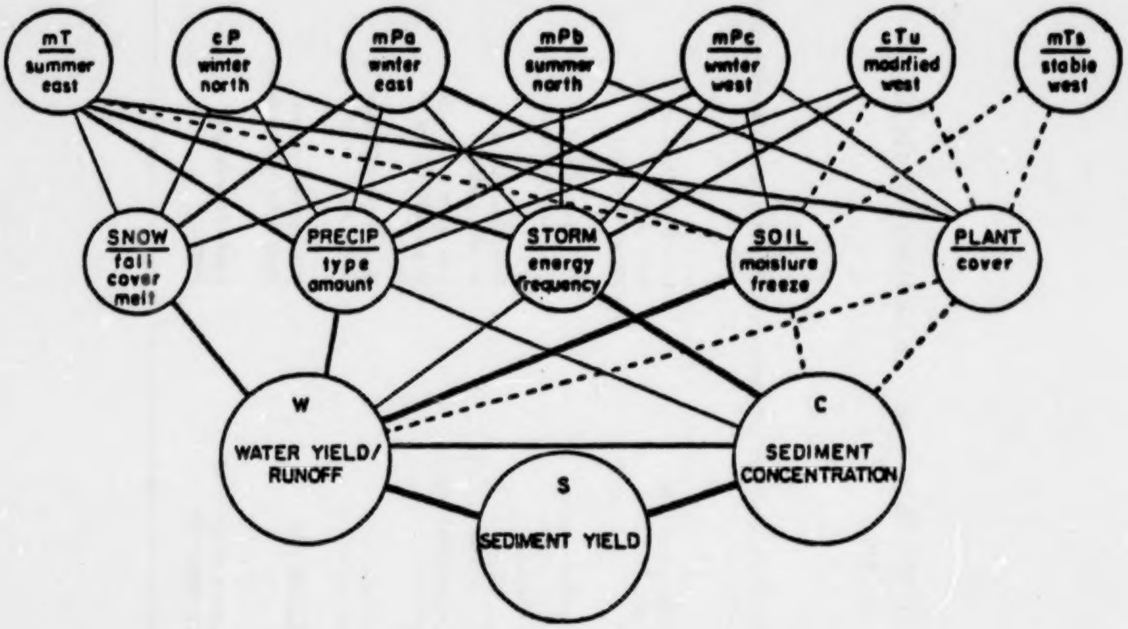
mT
summer
east
cP
winter
north
mPa
winter
east
mPb
summer
north
mPc
winter
west
cTu
modified
west
mTs
stable
west
SNOW
fall
cover
melt
PRECIP
type
amount
STORM
energy
frequency
SOIL
moisture
freeze
PLANT
cover
W
WATER YIELD/
RUNOFF
C
SEDIMENT
CONCENTRATION
S
SEDIMENT YIELD

Figure 2-13. Relation of Air Mass Types to Sediment Yield
(Source: Wilson, 1977)

Table 2-2. Relation of Air Mass Types to Sediment Yields (Source: Wilson, 1977)

Air mass controls of water yield or runoff (*W*), suspended sediment concentration (*C*), suspended sediment yield (*S*)

Air mass	*W*	*C*	*S*
mT (summer)	Moderate; limited by loss to soil, plants, despite much rain	Low; limited by plant cover despite high storm energy, frequency	Low; limited by low *W*, low to moderate *C*; vulnerable to very poor land use practices
cP (winter)	Low during time of snow cover; after *cP* is gone melt *W* can be large	Very low, especially while snow on ground	Very low, largest when *W* is large
mPa (winter east)	Very large if melt or rain is large, soils wet	Low, especially while snow on ground	Moderate; largest when *W* is large
mPb (summer)	Low-moderate; limited by loss to soil, plants	Low-moderate, limited by plant cover, few storms	Low-moderate; very vulnerable to improper land use practices
mPc (winter west)	Very large if melt or rain is large, soils wet	Moderate to high from rain; low from melt	Moderate to very large, especially when heavy rains follow dry season
cTu (modified summer)	Limited by little rain, dry soils	Very high due to poor plant cover, intense storms	Low if *W* very low, otherwise moderate to very large
mTs (stable summer)	Virtually none, except from antecedent conditions	Limited due to rare storms	Low because rain, runoff limited

Figure 2-14, based on regression analysis of 100 basins in the United States, illustrates the use of air masses on the SHG. In conclusion, Wilson writes:

> Where sediment yield data are absent or inadequate, it may be useful to evaluate the climatic variables occurring in a given basin and to rough out the probable SHG for that basin. This will be facilitated if the general shape of the SHG can be approximated by using data obtained from a gauged stream with the same climatic regime.
>
> Given the approximate SHG, it will be possible to identify seasons in which field measurements will be especially critical if sediment transport relationships are to be established and sediment yield is to be predicted with some accuracy. Sampling will be most important when sediment movement is large and variable. This situation will occur most commonly during periods when sediment concentrations are large, but runoff is not. In terms of the SHG, periods plotting above and to the left of other periods will be of most interest. In Figure 2-14, months which are expected to plot in the vicinity of cTu and mPb would properly be the focus of rather intensive sampling, in order to capture the inherent variability of sediment transport, and to estimate the large volume of sediment transport expected to occur.
>
> In contrast, comparatively little sampling would be needed for periods in which there is little sediment movement. These months plot towards the bottom of the SHG. Similarly, during high flow periods when sediment transport is relatively steady, it should be possible to evaluate sediment yield with only a few samples. These periods will plot to the right of the SHG. For all periods of interest, samples taken early in the season will be more important than those taken later, because of the fact that the early flows tend to be the more turbid.
>
> These procedures outlined above have not been applied, nor worked out in detail. However, it seems reasonable to expect that by recognizing seasonal patterns in sediment transport relationships, fairly reliable sediment yield estimates could be made based on a small number of carefully planned samples (perhaps only a few dozen), provided that runoff quantities can be estimated with some accuracy. Extensive data gathering efforts, such as the daily sampling often employed in the USA, are not essential unless extremely accurate transport curves are needed. Rather, a more limited sampling program can normally provide effective results, with consequent savings of limited funds and manpower.

In a paper on river sediment in the Atlantic coast drainage, R.H. Meade illustrated spatial and seasonal differences between four rivers draining to the Atlantic (Meade, 1982). Two of the rivers, the Juniata (PA) and the

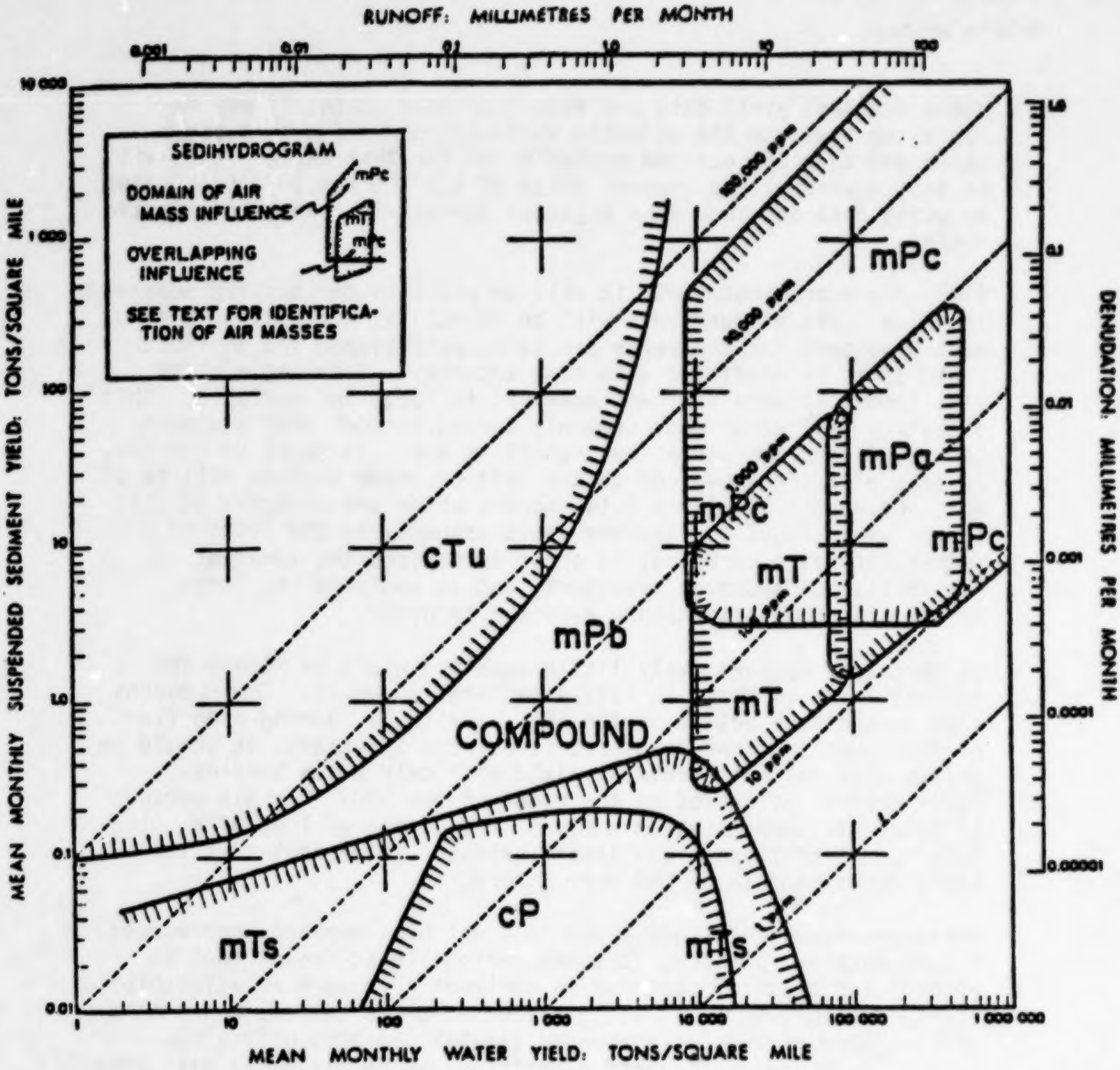

Figure 2-14. Generalized Sediment Transport and Yield Conditions Associated With Common U.S. Air Masses (Source: Wilson, 1977)

Yadkin (NC), carry more sediment in the summer than in the winter for a given stream discharge. The other two rivers, the Merrimack (MA) and the Edisto (SC), do not exhibit this tendency. For three of the four rivers, it can be said that suspended sediment is postively related to stream discharge. For all four, flows in winter are higher than those in summer (this fact corresponds well, incidentally, with the sedihydrograms developed by Wilson, 1977). The measured ranges of sediment concentration for the Juniata, Merrimack, Yadkin, and Edisto Rivers are, respectively, 1-700 mg/l, 1-290 mg/l, 20-1900 mg/l, and 3-60 mg/l. The approximate median concentrations in mg/l are, in the same order, 25, 10, 85, and 7 for winter (cool season) and 15, 9, 130, and 9 for summer (warm season).

Meade analyzed the graphs as per region:

> The sediment-streamflow relations show some strong contrasts from one river basin to another. In the two rivers in the northern Atlantic states, sediment concentration is closely related to streamflow during both seasons in the Juniata River (Fig. 2-15a), but apparently only during the cool season in the Merrimack River (Fig. 2-15b). The poorer relation between concentration and streamflow in warm season and the generally low concentration during most of the year in the Merrimack probably reflect the lower sediment yields that are typical of the rivers of New England and other areas that were intensely glaciated during the most recent ice age. Concentrations are consistently highest and increase most sharply with streamflow in rivers of the southern Piedmont (Fig. 2-15c); because of these consistently high concentrations, the sediment yields from the Piedmont are consistently the highest per unit area of any physiographic province on the Atlantic slope. In the southern Coastal Plain, by way of contrast, sediment concentrations are consistently low at all discharges (Fig. 2-15d) and the sediment yields per unit area are among the lowest on the Atlantic slope. The southern Coastal Plain is typically a lowlying area of permeable soil and poorly consolidated bedrock in which, even though rainfall is often more intense than on the Piedmont, streams respond more sluggishly to storms.

In an analysis of sediment problems in the Savannah River Basin, Meade (1976) analyzed discharge versus suspended sediment concentration and distinguished between two physiographic regions (Figure 2-16). Meade concluded that a Piedmont stream can be expected to carry about 10 times

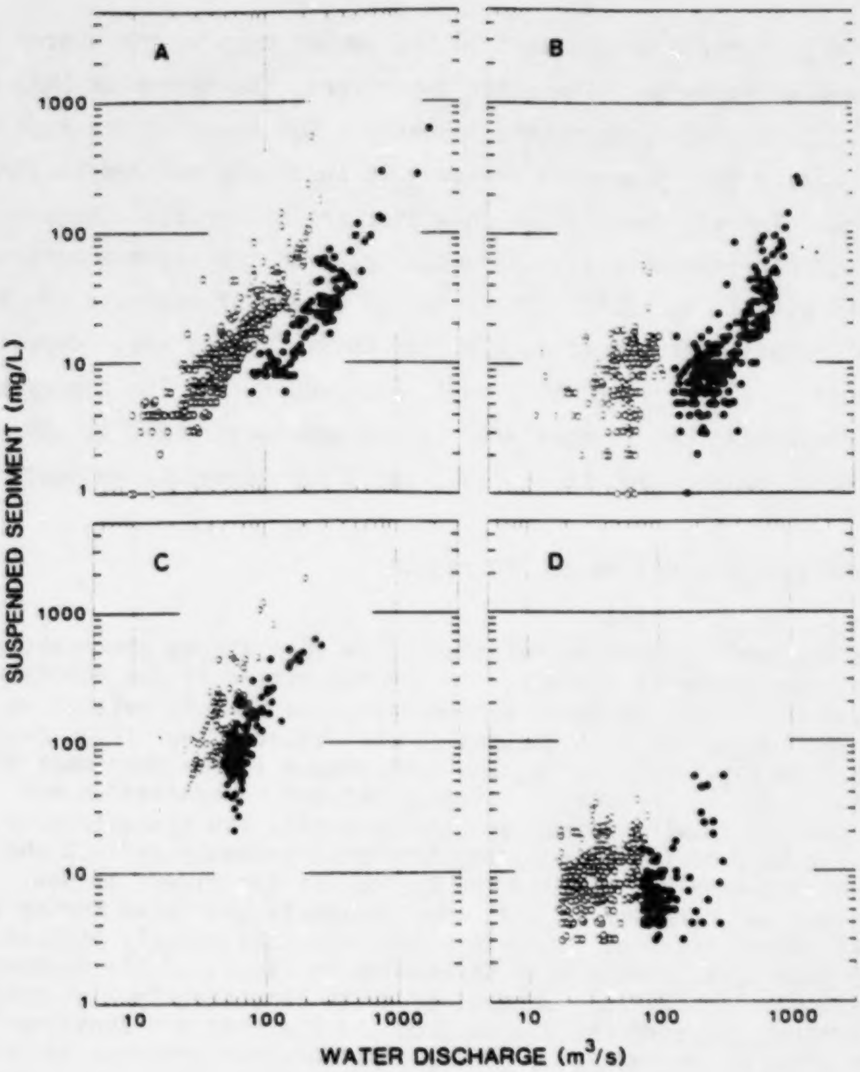

Figure 2-15. Suspended Sediment Concentration Versus Water Discharge for: A) Juniata River at Newport, PA; B) Merrimack River at Lowell, MA; C)Yadkin River at College, NC; D) Edisto River near Girhans, SC. (Dark circles represent cool season, open circles warm season. Source: Meade, 1982)

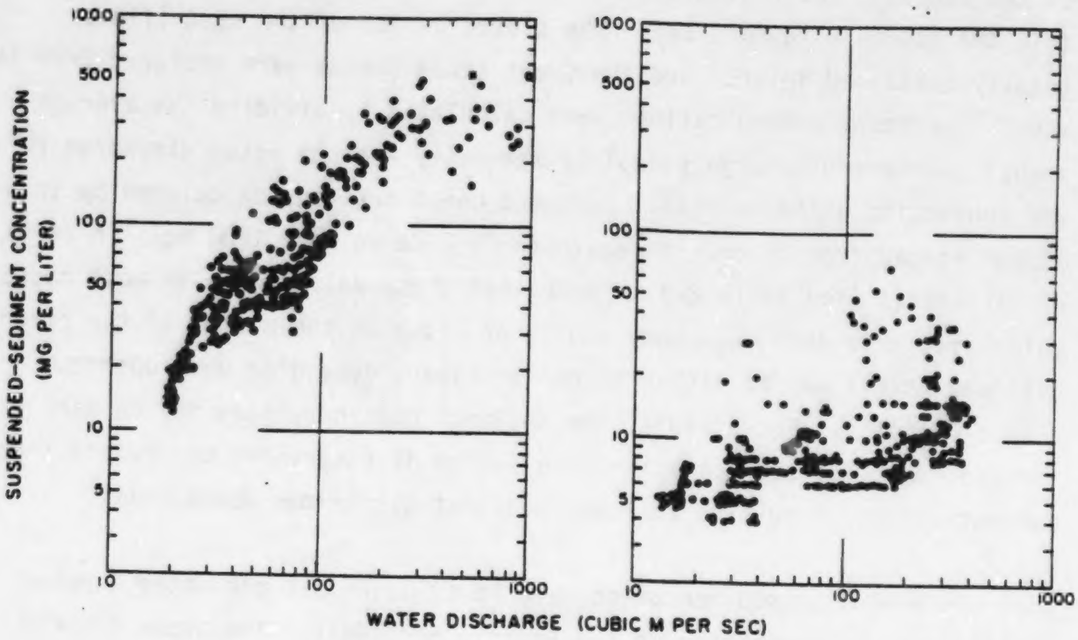

Figure 2-16. Suspended Sediment-Water Discharge Relationships for a Piedmont Stream (left) and a Coastal Plain Stream. (Source: Meade, 1976)

the concentration of suspended sediment that a Coastal Plain stream would carry at the same water discharge.

In 1973, Curtis, et al. published a pamphlet on fluvial sediment discharge to the oceans. The nation was divided into 27 drainage basins which drain into the oceans (Figure 2-17). The closed basins of the west (flows totally contained inland) and the Great Lakes Basins were excluded from the study. Sediment concentrations were calculated by dividing the average annual sediment discharge (tons) by the daily average water discharge (cfs) and converting units to mg/l. Sediment concentrations calculated by this method ranged from 15 mg/l in southern Florida to over 1600 mg/l in parts of California (see Table 2-3). Note that these values were in most cases calculated from data near the coast, or close to the mouths of the rivers. Upstream levels may be either higher or lower, depending upon upstream characteristics. For example, the sediment concentrations may be very high far upstream, but sedimentation in a series of reservoirs may reduce these concentrations, resulting in lower sediment discharges downstream.

At a conference on sedimentation held in 1970, Thomas presented a paper dealing with sedimentation in the Pacific Northwest. The paper covered sediments in the Columbia River Basin, the portions of the Closed and Klamath Basins located in Oregon, and the Washington and Oregon coastal drainage systems.

Data indicate that sediment concentrations are generally low west of the Cascades, averaging about 25 mg/l in times of low flow and from 200 to 300 mg/l during flood periods, with a recorded maximum of 800 mg/l. Much of the sediment is deposited in the many reservoirs and at other control projects located in the region.

Sediment concentrations may be significantly higher in the smaller streams east of the Cascades, where increased agriculture has increased erosion rates. No concentrations are given for these smaller streams, but excessive sedimentation has been discovered where these small streams enter reservoir waters. Again, widespread regulation of flows probably helps cut down on sediment concentrations further downstream.

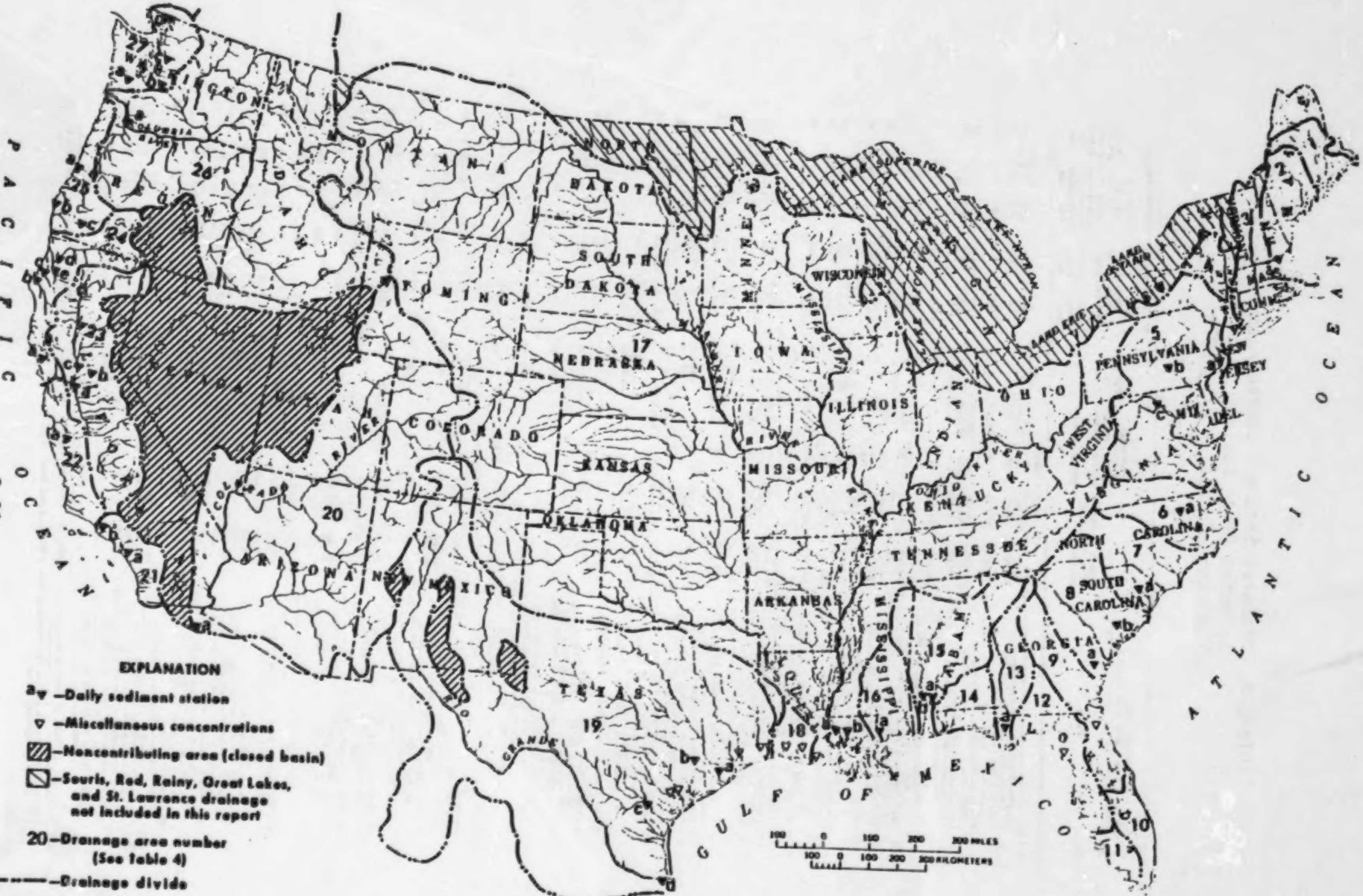
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
EXPLANATION
a▼ —Daily sediment station
▽ —Miscellaneous concentrations
▨—Noncontributing area (closed basin)
▧—Souris, Red, Rainy, Great Lakes, and St. Lawrence drainage not included in this report
20—Drainage area number (See Table 4)
—Drainage divide
100 0 100 200 300 MILES
100 0 100 200 300 KILOMETERS
WASHINGTON
OREGON
IDAHO
MONTANA
WYOMING
NEVADA
UTAH
COLORADO
ARIZONA
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
ILLINOIS
MICHIGAN
INDIANA
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
OHIO
PENNSYLVANIA
WEST VIRGINIA
VIRGINIA
NORTH CAROLINA
SOUTH CAROLINA
NEW JERSEY
MD.
DEL.
MASS.
CONN.
LAKE SUPERIOR
LAKE HURON
LAKE MICHIGAN
LAKE ERIE
LAKE ONTARIO
COLUMBIA RIVER
COLORADO RIVER
OHIO RIVER
MISSOURI RIVER
MISSISSIPPI RIVER
RIO GRANDE
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Figure 2-17. Drainage Area and Location of Sediment Sampling Stations (Source: Curtis et al., 1973)

Table 2-3. Measured Sediment Concentrations for Selected River Basins (Source: Curtis et al., 1973)

Drainage area (See figure 1 and table 6 for location.)				Water discharge		Period of record	Average annual suspended-sediment—				
No.	Name	Square kilometers	Square miles	Cubic meters per second	Cubic feet per second		Discharge, in thousands of tons per year: Metric tons	Discharge, in thousands of tons per year: Short tons	Yield, in tons per square kilometer or square mile: Metric tons	Yield, in tons per square kilometer or square mile: Short tons	Concentration, in milligrams per liter
	A. Atlantic Ocean										
1.	Passamaquoddy Bay to Penobscot Bay	30,047	11,601	668	23,600	......	417	460	13.9	39.6	20
2.	St. George River to Cape Cod Bay	54,134	20,901	1,162	41,030	......	1,179	1,300	21.8	62.2	32
3.	Cape Cod Bay to New York-Connecticut State line	46,537	17,968	986	34,818	......	780	860	16.8	47.9	25
4.	New York-Connecticut State line to Cape May	50,391	19,456	928	32,770	......	970	1,070	19.2	55.0	33
5.	Cape May to Cape Henry	205,262	79,250	2,866	101,200	......	5,262	5,800	25.6	73.2	58
	a. Delaware River at Trenton, N. J.	17,560	6,780	......	......	1950-69	680	749	38.7	111	----
	b. Susquehanna River at Harrisburg, Pa[1]	62,419	24,100	......	......	1964-68	1,771	1,952	28.4	81.0	----
	c. Potomac River at Point of Rocks, Md	24,996	9,651	......	......	1961-69	713	786	28.5	81.4	----
6.	Cape Henry to Neuse River	73,199	28,262	770	27,200	......	1,361	1,500	18.6	53.1	64
	a. Tar River at Tarboro, N.C	5,542	2,140	......	......	1959-67	105	116	19.0	54.1	----
7.	Cove Sound to Black River	75,247	29,053	660	23,400	......	1,270	1,400	16.9	48.2	50
	a. Pee Dee River at Pee Dee, S. C	22,870	8,830	......	......	1967-69	401	442	17.5	50.1	----
8.	Santee River to Sapelo Island	102,525	39,585	1,028	36,290	......	943	1,040	9.2	26.3	30
	a. Ogeechee River near Eden, Ga	6,863	2,650	......	......	1962-64	55.9	61.6	8.1	23.2	----
	b. Edisto River near Givhans, S. C	7,071	2,730	......	......	1967-69	19.1	21.1	2.7	7.7	----
9.	Altamaha River to Cape Kennedy	77,170	29,796	722	25,500	......	580	640	7.5	21.5	25
10.	Cape Kennedy to Cape Sable	E29,267	E11,300	255	9,000	......	122	134	4.2	11.9	15
	Total or annual average	743,760	287,166	10,180	359,460	......	12,886	14,204	17.3	49.5	40
	B. Gulf of Mexico										
11.	Cape Sable to Alligator Creek	E16,840	E6,500	71	2,500	......	33.6	37.0	2.2	6.2	15
12.	Peace River to New River	67,589	26,100	770	27,200	......	363	400	5.4	15.3	15
13.	Apalachicola River	51,800	20,000	764	26,700	......	354	390	6.8	19.5	15
	a. Apalachicola River at Chattahoochee, Fla	44,548	17,200	......	......	1967-69	157	173	3.5	10.1	----
14.	Wetappo Creek to Perdido River	36,778	14,200	711	25,100	......	907	1,000	24.6	70.4	40
15.	Mobile Bay	114,737	44,300	1,818	64,200	......	6,259	6,900	54.6	156	109
	a. Tombigbee River near Jackson, Miss	49,729	19,200	......	......	1962-64	2,226	2,454	44.8	128	
	b. Alabama River at Claiborne, Ala.	56,980	22,000	......	......	1955-69	2,293	2,528	40.2	115	----
16.	Pascagoula River to Pearl River	51,023	19,700	883	31,200	......	2,268	2,500	44.5	127	81
	a. Pearl River near Bogalusa, La.	17,172	6,630	......	......	1967-69	799	881	46.5	133	----
17.	Mississippi River	*3,268,340	*1,262,000	18,400	650,000	......	296,188	326,488	90.6	259	510
	a. Mississippi River at Red River Landing (see text)	2,923,861	1,129,000	......	......	1950-69	222,168	244,900	76.0	217	----
	b. Atchafalaya River (see text)	....	....	......	......	1950-69	73,907	81,467	......	......	----
18.	Vermilion, Mermentau, and Calcasieu Rivers	22,533	8,700	300	10,600	......	816	900	36.2	103	86
19.	Sabine River to Rio Grande	875,938	338,200	1,407	49,700	......	36,400	40,124	41.6	119	820
	a. Brazos River at Richmond, Tex.	114,012	44,020	......	......	1966-69	15,893	17,519	139	398	----
	b. Colorado River at Columbus, Tex.	106,371	41,070	......	......	1957-69	1,901	2,096	17.9	51	----
	c. Nueces River near Three Rivers, Tex	40,404	15,600	......	......	1961-62	445	491	11.0	31.5	----
	d. Arroyo Colorado at Mercedes, Tex.; Rio Grande near Brownsville, Tex., North Floodway near Sebastian, Tex.	N.d.	N.d.	N.d.	N.d.	1966-69	1,229	1,355	N.d.	N.d.	----
	Total or annual average	4,504,528	1,739,200	25,129	887,400	......	343,080	378,179	76.1	217.4	433
	C. Pacific Ocean										
20.	Colorado River	634,550	245,000	1.8	64	......	9.6	10.6	0.015	0.04	165
	a. Colorado River at Miguel C. Rodriguez, Mexico	634,550	245,000	1.8	64	1966-69	9.6	10.6	0.015	.04	----
21.	Tia Juana River to Ventura River	31,572	12,190	14	500	......	730	805	23.1	66	1,634
	a. San Juan Creek near San Juan Capistrano, Calif	275	106	......	......	1967-68	85.5	94.3	311	890	----
	b. Santa Clara River at Saticoy, Calif	4,131	1,595	......	......	1968	68.7	75.7	16.6	47.5	----
22.	San Jose Creek to Pescadero Creek	28,821	11,129	68	2,400	......	3,320	3,660	115	329	1,548
	a. Salinas River near Spreckels, Calif	10,767	4,157	......	......	1966-68	531	586	49.3	141	----
23.	San Francisco Bay	*123,286	*47,570	861	30,400	......	3,252	3,585	26.4	75.4	120
	a. San Joaquin River near Vernalis, Calif	35,069	13,540	......	......	1966-69	350	386	10	28.5	----
	b. Cosumnes River at Michigan Bar, Calif	1,386	535	......	......	1963-69	143	158	103	295	----
	c. Sacramento River at Sacramento, Calif	60,943	23,530	......	......	1957-69	2,466	2,719	40.4	116	----
24.	Lagunitas Creek to Smith River	56,514	21,820	1,190	42,100	......	61,531	67,816	1,089	3,108	1,630
	a. Russian River near Guerneville, Calif	3,471	1,340	......	......	1958-69	4,134	4,558	1,191	3,402	----
	b. Eel River at Scotia, Calif	8,063	3,113	......	......	1958-69	26,621	29,346	3,302	9,428	----
	c. Mad River at Arcata, Calif	1,256	485	......	......	1957-69	2,441	2,691	1,944	5,549	----
	d. Klamath River at Orleans, Calif	22,015	8,500	......	......	1967-69	2,387	2,631	108	310	----
	e. Trinity River near Hoopa, Calif[2]	7,420	2,865	......	......	1958-69	4,987	5,497	672	1,919	----
25.	Oregon coastal area	42,771	16,500	1,500	53,300	......	2,903	3,200	68.3	196	63
	a. Siuslaw River near Mapleton, Oreg	1,523	588	......	......	1960-69	104	114	68.3	193.9	----
	b. Sixes River at Sixes, Oreg	300	116	......	......	1965-69	199	220	663	1,897	----
	c. Rogue River at Raygold, Oreg	5,317	2,053	......	......	1918	59.2	65.3	11.1	31.8	----
26.	Columbia River	668,738	258,200	7,062	251,200	......	14,170	15,620	21.2	60.5	66
	a. Columbia River at Vancouver, Wash	624,190	241,000	......	......	1964-69	9,704	10,697	15.5	44.4	----
27.	Naselle River to Nooksack River	50,790	19,610	2,523	89,100	......	3,873	4,270	76.3	218	48
	a. Chehalis River at Porter, Wash	3,351	1,294	......	......	1962-69	115	127	34.3	97.8	----
	b. Skykomish River at Monroe, Wash	2,160	834	......	......	1967-69	244	269	113	323	----
	c. Snoqualmie River near Carnation, Wash	1,562	603	......	......	1968-69	263	290	168	481	----
	d. Skagit River near Mt. Vernon, Wash	8,011	3,093	......	......	1910	330	364	41.2	118	----
	Total or annual average	1,637,942	632,410	14,121.8	499,000	......	89,872.2	99,068.6	54.9	156.6	201

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[1] Three dams between station and mouth of river (Williams and Reed, 1972).
[2] Tributary to Klamath River.

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2.5 RATES OF EROSION AND SEDIMENT LOADING

Loehr, et al. (1979) have estimated nonpoint contributions of sediment to surface waters, in million tonnes (1 tonne equals 1.1 tons) per year, as follows:

Cropland	1,700
Pasture and range	1,190
Forest	232
Construction	179
Mining	54
Urban runoff	18
Rural roadways	2
Natural (background)	1,150
Total	4,525

Of these sources, agricultural accounts for about 65% of the total, cultural activities account for 75%, and natural loadings account for about 25%. Novotny and Chesters (1981) estimate that over 4 billion tons of sediment are delivered annually into streams and rivers of the United States, almost half of which originates from approximately 170 million hectares of agricultural land.

Brant, et al. estimate that the average rate of natural erosion is 40 tonnes/km^2/year; that agricultural erosion may range from 100 to 4,000 tonnes/km^2/year; while sediment yields from urban developing areas may reach values of 50,000 tonnes/km^2/year.

The total sediment load in a stream may be divided ino bedload and washload, where washload refers to the suspended fraction. Measurements of sediment movement in lowland, largely agricultural areas indicate that washload may account for 90% to 95% of the total sediment load (Novotny and Chesters).

2.6 IMPACTS OF ANTHROPOGENIC SUSPENDED SEDIMENT

The impacts of urbanization and other development have been shown to both accelerate and reduce natural erosion processes. Some of the most significant increases in suspended sediment have occurred by disturbing the soil through agricultural, strip mining, and construction activities. On the other hand, many activities in the arid southwest reduce suspended sediment through the introduction of vegetative cover for agriculture and by trapping sediment in reservoirs. In addition to being a major pollutant in itself, sediment serves as a carrier for other pollutants such as adsorbed phosphorous, nitrogen, and other organic compounds, and for toxics such as pesticide residue and metals.

Meade (1969) estimated that the conversion of forest land to farms in areas around the Potomac and Susquehanna River basins near Washington, D.C. caused about a tenfold increase in sediment yield. It is estimated that logging activities in Oregon and California yield three times as much sediment per unit area as forested land (Meade, 1969).

Camp Dresser & McKee (1983), in a study of the effects of urbanization in Northern Virginia, compiled data on annual sediment loading rates ranging from under one ton per acre per year (t/a/y) for naturally vegetated areas to from one to three t/a/y for stabilized urban areas, and 50 to 100 t/a/y for uncontrolled urbanizing areas.

In addition to overland soil loss, urbanization can cause instability in the stream channels themselves. Higher peak discharges and runoff volumes resulting from developing areas increase the erosive forces on the channel banks.

Man's activities affect sediment concentrations in different ways. It is well known that construction/urbanization activities tend to increase sediment concentrations many-fold. However, the construction of reservoirs to harness hydroelectric potential and/or control flooding has brought about a decrease in sediment concentrations in many places. Meade reported (1982):

> Two examples from the Atlantic drainage show the reduction in sediment that can be caused by reservoirs on the principal rivers. A before-and-after example is provided by the data collected from the Roanoke River at Scotland Neck, North Carolina, before and after the completion of a large flood-control reservoir about 125 km upriver in 1952 (Figure 2-18). Concentrations of suspended sediment at equivalent water discharges were about an order of

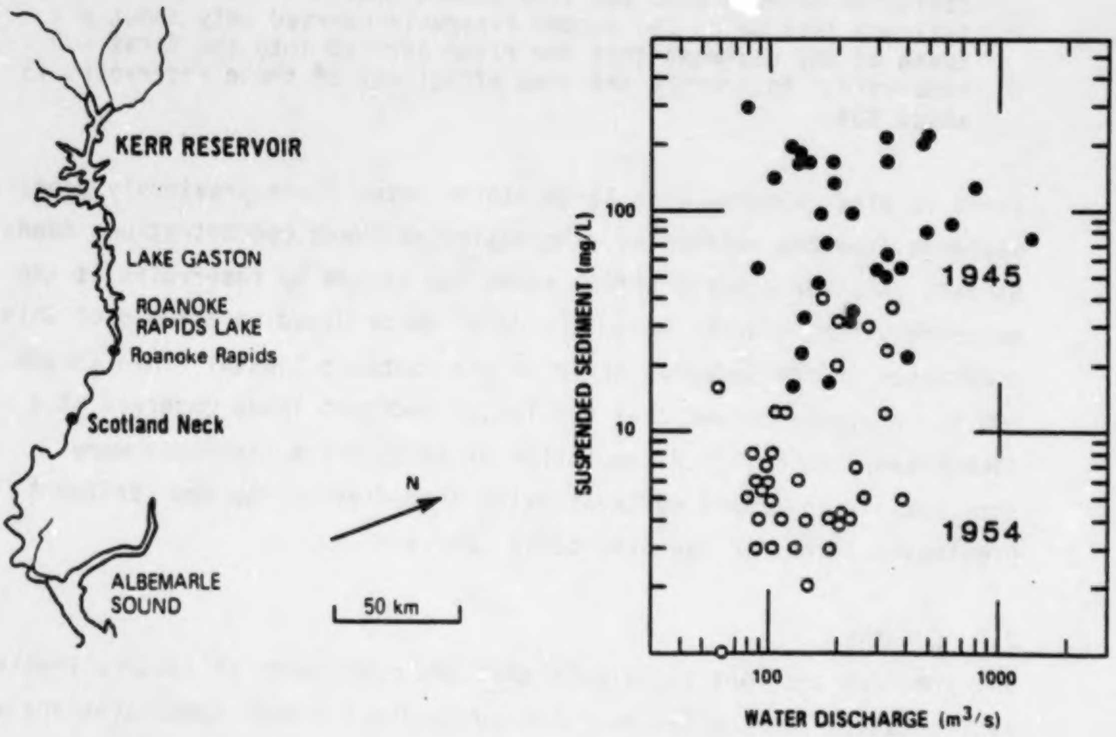

Figure 2-18. Comparison of Suspended Solids Concentrations in Roanoke River at Scotland Neck, NC, Before (dark circles) and After (open circles) Kerr Reservoir was Completed in 1952. Note: Lake Gaston and Roanoke Rapids Lake were not formed until after 1954. (Source: Meade, 1982)

> magnitude smaller after the reservoir was completed than they had been before. This suggests that Kerr Reservoir effectively trapped about 90% of the sediment that the Roanoke formerly carried past Scotland Neck.
>
> An inflow-outflow example is shown in Figure 2-19. A pair of reservoirs was completed in 1941 to generate hydroelectric power from the waters of the lower Santee River of South Carolina. Data collected between 1966 and 1968 showed that the water in the tailrace just below the second reservoir carried only about a tenth of the sediment that the river carried into the first reservoir. Apparently the trap efficiency of these reservoirs is about 90%.

There is also evidence that large storms often flush previously deposited sediment from the reservoirs, increasing sediment concentrations downstream. Another adverse effect sometimes caused by reservoirs is the scouring of the channel below the dam. Meade cited an example of this occurrence on the Savannah River in the southern Coastal Plain (Meade, 1982). Analysis showed that the larger sediment loads observed at a downstream station after completion of an upstream reservoir were attributable to stored sediment being eroded below the dam (sediment previously stored in the bed, banks, etc.).

2.7 SUMMARY

The previous sections illustrate that the components or factors involved in sedimentation are complex and that suspended sediment concentrations vary both spatially and temporally.

Although each individual process in landform development is deterministic in itself, the complexity of the interrelationship between climate, geology, the influence of vegetation, and the chance occurrence of governing events on landforms is such that the exact instantaneous sediment discharge is difficult to predict.

It is not unreasonable to assume, however, that particular basin characteristics, although varying from one basin to another, will belong to a well defined unique distribution as determined by local climate and geology and that these characteristics are indices to hydrologic behavior and sedimentation. Regardless of geographic location, lithologically similar land

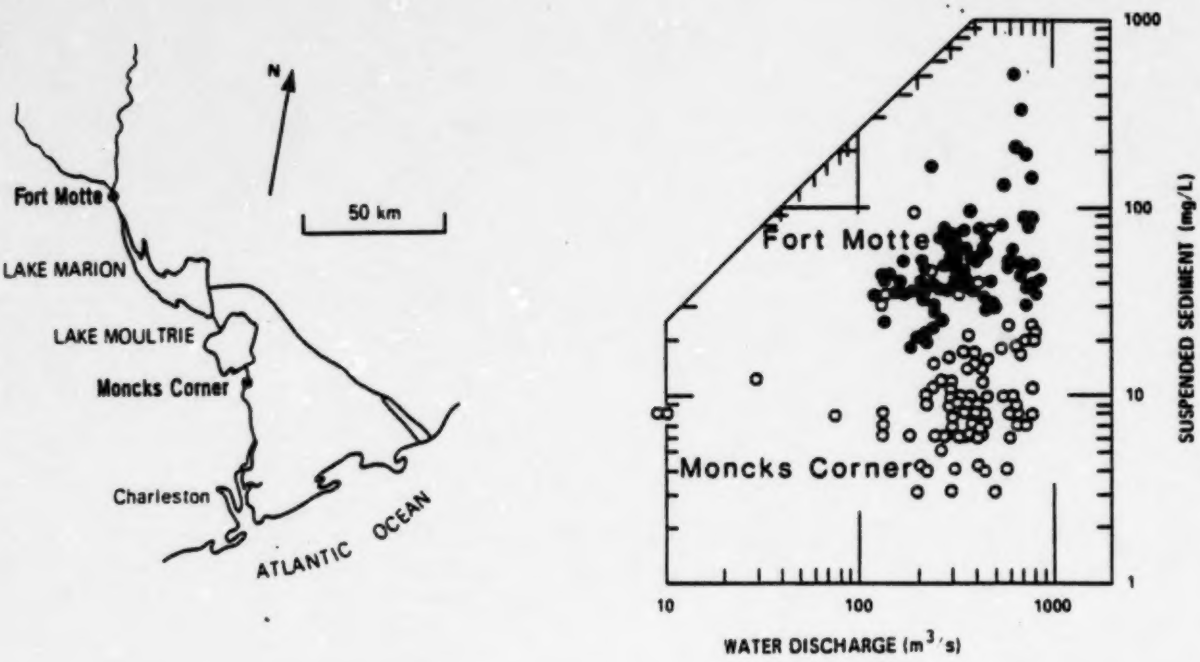

Figure 2-19. Comparison of Suspended Sediment Concentrations in the Santee River, SC, Before Entering (dark circles) and After Leaving (open circles) Two Large Reservoirs. (Source: Meade, 1982)

areas subjected to comparable climate exposure and land uses will display similar suspended sediment concentrations.

3.0 IMPACTS OF SUSPENDED SOLIDS ON AQUATIC LIFE

3.1 INTRODUCTION

In the discussion to follow, the effects of suspended sediment on aquatic life have been divided into the general categories of lethal and sublethal effects. Lethal effects are those which are directly associated with the death of the biota. Such effects are generally not difficult to quantify, as the endpoint is defined by the organism's death. Sublethal effects include consequences of suspended sediment that may be harmful to biota in terms of overall survival, such as effects on feeding and reproduction. These cause-effect relationships are more difficult to assess in short-term laboratory tests.

The lethal and sublethal categories provide a parallel to the ambient water quality criteria that provide for the protection of aquatic life from acute and chronic effects. The terms acute and chronic will not be used in this report because these terms both imply health effects. Since suspended sediment in a stream may have deleterious effects on aquatic life that are not necessarily health effects, it was felt that the term 'chronic' should not be used.

Lethal effects are generally studied with regard to consequences to fish, although suspended sediment may also be directly responsible for deaths of zooplankton and macroinvertebrates. Suspended sediment acts directly upon the gills of fish. The gill filaments and the secondary lamellae act as a sieve that traps particles that subsequently clog the gill, resulting in asphyxiation (O'Connor, et al., 1976). Sediment that has settled from the water column may also have a lethal effect, smothering bottom-dwelling organisms and fish eggs. The effects of sedimentation will not be discussed in detail in this report although they do have important consequences to aquatic life.

Suspended sediment causes a variety of sublethal and other effects, including consequences to feeding, reproduction and physiological processes of organisms. Feeding of zooplankton and macroinvertebrates may be inhibited, eventually causing starvation. An increase in macroinvertebrate drift may be caused by increases in solids concentrations and sedimentation. Fish are also affected by the loss of zooplankton and macroinvertebrates, which are important constituents of fish diets. In addition, increased turbidity inhibits fish feeding by obscuring prey from the view of sight-feeding fish.

Suspended sediment may delay the development of fish eggs, and reduce the growth of larval fish. Such sublethal effects put fish at a competitive disadvantage. Other consequences of high suspended sediment concentrations are reduced resistance to disease and damage to gill tissues. Gill damage caused by suspended matter reduces the respiratory surface area and interferes with oxygen-carbon dioxide transport. O'Connor, et al. (1977) measured several parameters which change in response to interference with oxygen-carbon dioxide exchange. High suspended sediment concentrations evoked responses similar to those observed when fish are deprived of sufficient oxygen: increased blood cell count, increased hematocrit, and increased hemoglobin concentration in the blood. Increases in these parameters raise the blood's oxygen exchange capacity.

Although sedimentation effects will not be covered in detail in this report, it is important to recognize that habitat changes caused by the scouring and filling of pools and riffles affect the success of species propagation. Sediment deposition affects the permeability of gravel, water circulation, and dissolved oxygen levels, which in turn affect the suitability of an area for spawning. Loss of spawning grounds is a major contributor to the decline of fish populations.

Several factors should be considered when the effects of suspended sediments are examined. Rogers (in O'Connor, et al., 1976) concluded that the lethal effect of suspended sediment is dependent on particle shape and angularity rather than on size. This relationship may result from angular particles having a greater affinity for the gill surface, thereby causing abrasions or anoxia. Other investigators have also documented varying effects for different types of sediment suspensions (European Inland Fisheries Advisory Committee, 1964; O'Connor, et al., 1976).

The organic content of suspended sediments can influence the effect of sediments on aquatic life. Sediments containing a large fraction of organic material may significantly deplete dissolved oxygen as the organic fraction decays. Toxics sorbed to sediment particles may also affect the consequences of suspended sediment to aquatic organisms, and sorbed toxics may be resolubilized when bottom sediments are resuspended.

The lethal effects of suspended sediment on fish species may be different for different stages in the life history. Juveniles are generally more susceptible to suspended sediment than are adults. Thus, it is important to consider the lifestage that is present during conditions of high flow and increased suspended sediment concentrations.

The following sections contain information concerning the effects of various suspended sediment concentrations and turbidities on aquatic life. Both lethal and sublethal effects on primary producers, zooplankton, macroinvertebrates, and fish are included. The studies that are reviewed in this report examine the effects of inert particles on aquatic biota, and do not include data on contaminated or highly organic sediments.

3.2 EFFECTS OF SUSPENDED SEDIMENT ON PHYTOPLANKTON AND ZOOPLANKTON

Although many studies report decreases in primary productivity because of increases in suspended sediment in water bodies, there is a paucity of information in the literature that quantifies changes in primary production caused by known solids concentrations. Similarly, the effects on zooplankton are rarely quantified, while the lethal concentration of suspended sediment to zooplankton is essentially unknown.

Van Nieuwenhuyse (1983) studied the effects of turbidity and settleable solids on the productivity of benthic algae. The cause of increased turbidity in the Alaskan streams, examined in this study, was sediment from placer mining operations. Moderately mined streams, which generally contained settleable solids concentrations less than 0.1 mg/l (mean turbidities below 200 NTU), exhibited nearly twice the productivity of heavily mined streams. Settleable solids concentrations in heavily mined streams averaged more than 0.2 mg/l.

The impact of suspended sediments on net plankton (larger than 20 um) has been studied by Buck (in Muncy, et al., 1979). Surface tows of clear ponds (suspended solids concentrations less than 25 ppm) yielded plankton volumes 8 times and 12.8 times greater than in intermediately turbid and muddy ponds, respectively. Ponds with suspended sediment concentrations between 25 ppm and 100 ppm were considered intermediately turbid, while muddy ponds had concentrations of more than 100 ppm suspended solids.

Nonsettleable solids concentrations of 10 mg/l did not inhibit the growth of the algae Scenedesmus abundans. Friant, et al. (1980) observed the effect of nonsettleable solids concentrations of 10 mg/l in a 7 day experiment, and concluded that there was no significant change in light transmission or growth of Scenedesmus abundans.

Photosynthesis in vascular aquatic plants is inhibited because of decreased light penetration caused by sediments. Furthermore, sediments that settle onto the leaves of aquatic plants may further reduce photosynthesis. Robel (in Muncy, et al., 1979) reported an inverse correlation between turbidity and production of sago pondweed (Potamogeton pectinatus). While the qualitative effect of suspended sediment on vascular plants is understood, there are few studies that correlate known sediment concentrations with measured effects.

Increased concentrations of suspended sediments also stress zooplankton. McCabe and O'Brien (1983) studied the effects of suspended silt on feeding of Daphnia pulex. Both filtering and assimilation rates were severely depressed at low concentrations of suspended silt and clay. A turbidity of only 10 NTU decreased filtering rates, and assimilation was decreased by more than 55 percent.

Arruda, et al. (1983) studied the effects of sediment on ingestion and rates of incorporation of algae by Daphnia sp. They observed a 70% decrease in efficiency when Daphnia, exposed for 1.5 hours, were fed in solutions containing 10 mg/l of sediment. There was an 85 percent reduction in the ingestion and incorporation rates when sediment levels were as low as 100 mg/l. Ingestion rates of Chlorella vulgaris by Daphnia parvula and D. pulex were decreased by 95 percent when suspended sediment concentrations were increased from 0.0 mg/l to 2,451 mg/l.

3.3 EFFECTS OF SUSPENDED SEDIMENT ON MACROINVERTEBRATES

Much of the information concerning the effects of suspended sediment on freshwater macroinvertebrates deals with macroinvertebrate drift. The term "drift" refers to the downstream transport of insects and other invertebrates in flowing waters. Rosenberg and Snow (1975) contend that drift and the subsequent decrease in standing crop is caused by sedimentation rather than suspended solids, although drift is often correlated with increases in suspended matter.

A study in which sediment was added to a river in Indiana showed increased invertebrate drift with increased suspended sediment concentrations (Gammon, in Rosenberg and Snow, 1975). Gammon reported that the numbers of drifting macroinvertebrates increased in a roughly linear fashion with increases in sediment concentration up to 160 mg/l. However, he did not attempt to explain decreases in numbers of invertebrates drifting at the two highest sediment concentrations tested (Table 3-1).

Sediment additions to riffles on the Harris River, Northwest Territories (Canada) revealed that concentrations as low as 100 mg/l, for a 15 minute duration, caused increased drift of a mixed invertebrate population, and a loss of 0.04 to 0.5 percent of the standing crop (Rosenberg and Wiens, 1975). Sediment concentrations of 250 mg/l (15 minute exposure time) caused a 2.6 percent loss of the standing crop of the macroinvertebrate population made up of Chironomidae, Ephemeroptera, Simuliidae, and Hydracarina.

McFarland and Peddicord (1980), and Peddicord (1980) studied the effects of suspended kaolin on some marine and estuarine macroinvertebrates in laboratory aquaria. Several species were shown to be relatively insensitive to suspended clay concentrations as high as 100 g/l. These species, which had 10 percent or less mortality during exposure times of 5 to 12 days, were:

TABLE 3-1

Percent Increases in Number of Drifting Macroinvertebrates Caused by Additions of Known Amounts of Suspended Sediment.

ADDED SOLIDS (mg liter^{-1})	% INCREASE IN NUMBERS DRIFTING
18.6	25.9
54.3	32.0
84.3	45.7
104.7	89.5
135.5	118.5
154.5	101.7
271.3	88.8

SOURCE: Gammon, in Rosenberg and Snow, 1975.

sea urchin (Strongylocentrotus purpuratus), Japanese clam (Tapes japonica), hermit crab (Pagurus hirsutiusculus), an isopod (Sphaeroma pentodon), mud snail (Nassarius obsoletus), blue mussel (Mytilus edulis), and two species of tunicates (Mogula manhattensis, Styela montereyensis) (Table 3-2).

Estimates for lethal concentrations of suspended kaolin for X percent of the animals, commonly known as the LCX, were made for some of the estuarine and marine species (McFarland and Peddicord, 1980). Time-concentration studies showed the tunicate Ascidia ceratodes to be one of the most sensitive species tested. The estimated 100-hour LCX values were: LC10 = 7 g/l, LC20 = 13 g/l, and LC50 = 38 g/l. Estimates of 200-hour LCX values for those species tested longer than 200 hours are presented in Table 3-3. Of those species whose responses are shown in Table 3-3, the tolerance of the dungeness crab decreased the most rapidly with time. Further research revealed that the mortality of dungeness crabs was associated with molting (Peddicord, 1980). The 25-day LC50 for molting crabs was estimated as 9 g/l. After 25 days of exposure to 4 g/l, 20 percent of the crabs that molted were expected to die (25-day LC20 = 4 g/l).

It is also important to recognize that sublethal responses to suspended sediment may affect the organism's growth and metabolism. For example, Sherk (in Rosenberg and Snow, 1975) reported that the pumping rates of adult oysters were reduced by more than 50 percent in suspended sediment concentrations of 0.1 g/l.

3.4 EFFECTS OF SUSPENDED SEDIMENT ON SALMONID FISH

The studies that are summarized in the following section deal primarily with the effects of suspended sediment on the various life stages of the salmonids. The effects of suspended sediment on various life stages encompassing the egg stage through the adult stage will be presented, and will include information on several species. Salmonids generally migrate to natal streams to spawn. For example, coho salmon (Oncorhynchus kisutch) are anadromous fish, native to the northern Pacific Ocean. They migrate from saltwater areas to natal streams to spawn from midsummer to winter, depending on latitude. Entry into freshwater streams often coincides with rises in streamflow (McMahon, 1983) and therefore often with high suspended

TABLE 3-2

Observed Mortalities of Species Relatively Insensitive to suspended Kaolin.

Species[a]	Exposure time in days	% Mortality at 100 g/L
Strongylocentrotus purpuratus (sea urchin)	9	0
Tapes japonica (Japanese clam)	10	0
Pagurus hirsutiusculus (hermit crab)	12	0
Sphaeroma pentodon (isopod)	12	0
Nassarius obsoletus (mud snail)	5	0
Mytilus edulis (blue mussel) (2.5 cm)	5	10
Mytilus edulis (blue mussel) (10 cm)[b]	11	10
Molgula manhattensis (tunicate)	12	9
Styela montereyensis (tunicate)	12	10

[a] Species grouped together were tested simultaneously in the same aquaria

[b] Tested simultaneously in the same aquaria with *Mytilus californianus*

SOURCE: McFarland and Peddicord, 1980.

TABLE 3-3

200-hr LCX Estimates, Equations, and Coefficients of Determination for those Species Tested Longer than 200-hr.

Species	200-hr LCX in g/L	Equations used for estimates	Coefficient of determination r^2
Mytilus californianus[a] (coast mussel)	LC10 = 26	$\ln Y = 22.3 - 3.59 \ln X$	0.93
	LC20 = 42	$Y = 115 - 0.349X$	0.89
	LC50 = 96	$1/Y = 0.020 - 1.93(1/X)$	0.75
Crangon nigromaculata (spot tailed sand shrimp)	LC10 = 16	$\ln Y = 5.01 - 0.0113X$	0.76
	LC20 = 28	$\ln Y = 5.04 - 0.00850X$	0.87
	LC50 = 50	$\ln Y = 7.96 - 0.756 \ln X$	0.98
Palaemon macrodactylus[b] (grass shrimp)	LC10 = 24	$\ln Y = 10.3 - 1.34 \ln X$	0.71
	LC20 = 77	$\ln Y = 4.94 - 0.00300X$	0.96
	LC50[c]		
Cancer magister (dungeness crab)	LC10 = 10	$\ln Y = 6.37 - 0.766 \ln X$	0.72
	LC20 = 18	$\ln Y = 7.01 - 0.766 \ln X$	0.96
	LC50 = 32	$\ln Y = 3.05 - 83.1(1/X)$	0.99
Neanthes succinea (polychaete)	LC10 = 9	$Y = 58.6 - 0.246X$	0.88
	LC20 = 22	$\ln Y = 4.51 - 0.00700X$	0.92
	LC50 = 48	$\ln Y = 5.91 - 0.386 \ln X$	0.91

[a] Tested simultaneously in the same aquaria with 10-cm *Mytilus edulus*

[b] Tested simultaneously in the same aquaria with *Anisogammarus confervicolus*

[c] Fifty % mortality was not reached

SOURCE: McFarland and Peddicord, 1980.

sediments. Older salmonids can survive high concentrations of suspended sediment for considerable periods, and acute lethal effects generally occur only if concentrations exceed 20,000 mg/l (Sorensen, et al., 1977; Cordone and Kelley, in Sigler, et al., 1984).

While direct and acute effects on fish are undeniably very important, the effects of sedimentation and siltation of spawning grounds are also critical for species propagation. Although the detrimental effects on eggs at spawning grounds are widely known, quantities of sediment causing fish to abandon redds are generally not documented.

Also important are those effects that may be categorized as sublethal, such as turbidity effects on sight-feeding fish. Turbid water may obscure the view of food, and thereby result in reduced growth rates for fish. The studies and bioassays that are reviewed in the following section record the direct effects of suspended sediment on fish, but may not reflect the effects of sedimentation on reproduction. Using data from a literature review by the European Inland Fisheries Advisory Commission (EIFAC, 1965), Sorensen, et al. (1977) have summarized the effects of suspended sediment on salmonid fish (Table 3-4). Effects on rainbow trout (*Salmo gairdneri*), Pacific salmon (*Oncorhynchus* spp.), brown trout (*Salmo trutta*), cutthroat trout (*Salmo clarkii*), Atlantic salmon (*Salmo salar*), and brook trout (*Salvelinus fontinalis*) are included.

3.4.1 EFFECTS ON EGG STAGE

Billard (1982) concluded that the presence of sediments in water does not prevent fertilization of trout (*Salmo gairdneri*) eggs. Laboratory studies were designed to expose eggs to sediment concentrations from 0 to 20 g/l for 1, 10 or 20 minutes. The fertilization rate declined significantly after the eggs were exposed for 10 minutes at 8°C to doses exceeding 1.2 g/l, probably because of clogging of the micropyle rather than the presence of sediment in the medium in which the gametes meet.

3.4.2 EFFECTS ON LARVAL STAGE

Steelhead (*Salmo gairdneri*, anadromous trout) fry were exposed to turbidities of 38 to 49 NTU for 14 to 19 days (Sigler, et al., 1984). The

TABLE 3-4

Summary of Effects of Suspended Solids on Salmonid Fish (Data taken from Review in EIFAC, 1965)

Fish (Species)	Effect	Concentration of Suspended Solids	Source of Suspended Materials	Comment
Rainbow Trout (Salmo gairdneri)	Survived one day	80,000 ppm	Gravel washing	
	Killed in one day	160,000 ppm	Gravel washing	
	50% mortality in 3 1/2 wks	4,250 ppm	Gypsum	
	Killed in 20 days	1000-2500 ppm	Natural sediment	Caged in Powder River, Washington 70% mortality in 30 wks
	50% mortality in 16 wks	200 ppm	Spruce fibre	
	1/5 mortality in 37 days	1,000 ppm	Cellulose fibre	
	No deaths in 4 wks	553 ppm	Gypsum	
	No deaths in 9-10 wks	200 ppm	Coal washery waste	
	20% mortality in 2-6 months	90 ppm	Kaslin and diatomaceous earth	Only slightly higher mortality than control
	No deaths in 8 months	100 ppm	Spruce fibre	
	No deaths in 8 months	50 ppm	Coal washery waste	
	No increased mortality	30 ppm	Kaslin or diatomaceous earth	
	Reduced growth	50 ppm	Wood fibre	
	Reduced growth	50 ppm	Coal washery waste	
	Fair growth	200 ppm	Coal washery waste	
	"Fin-rot" disease	270 ppm	Diatomaceous earth	
	"Fin-rot" disease	200 ppm	Wood fibre	
	"Fin-rot" disease	100 ppm	Wood fibre	Symptons after 8 months exposure
	No "fin-rot"	50 ppm	Wood fibre	
	Reduced egg survival	(Siltation)		
	Total egg mortality in 6 days	1000-2500 ppm	Mining operations	Eggs in gravel Powder River, Oregon (Not specifically rainbow trout eggs)
Pacific Salmon (Oncorhynchus)	Survived 3-4 wks	300-750 ppm (2300-6500 ppm for short periods each day)	Silt	Fingerlings

TABLE 3-4 (contd)

Summary of Effects of Suspended Solids on Salmonid Fish

Fish (Species)	Effect	Concentration of Suspended Solids	Source of Suspended Materials	Comment
	Reduced survivial of eggs	(Silting)		Eggs in gravel
	Supports populations	(Heavy loads)	Glacial silt	Spawn when silt is washed from spawning beds.
	Avoid during migration	(Muddy water)		Yuba River, California
Brown Trout (Salmo trutta)	Do not dig redds	(Sediment in gravel)		Water must pass through gravel
	Reduced populations to 1/7 of clean streams	1000-6000 ppm	China-clay waste	
Cutthroat Trout (Salmo clarkii)	Abandon redds	(If silt is encountered)		
	Sought cover and stopped feeding	35 ppm		Two hours exposure
Atlantic Salmon (Salmo salar)	No effect on migration	Several thousand ppm		River Severn, British Isles
Brook Trout (Salvelinus fontinalis)	No effect on movement	(Turbidity)		

SOURCE: Sorensen, et al., 1977.

turbidity, which was produced through the addition of fireclay and bentonite to water in laboratory channels, caused the fish to exhibit avoidance reactions. Although the turbidities examined were not lethal to the fish fry, steelhead in turbid-water channels were consistently smaller than fish in clear-water channels.

Sigler, et al. (1984) compared the responses of coho salmon (Oncorhynchus kisutch) fry in turbid-water channels (22-86 NTU) to responses of fry in clear-water channels. The fish that were exposed to the suspended fireclay and bentonite over an 11 to 15 day period were significantly smaller than the control fish in clear-water channels.

3.4.3 EFFECTS ON JUVENILES

Juvenile coho salmon were subjected to elevated concentrations of suspended sediment to test the threshold turbidity level that elicited avoidance (Bisson and Bilby, 1982). The juveniles did not avoid moderate turbidity increases, but exhibited significant avoidance when turbidity exceeded 70 NTU. Bisson and Bilby (1982) thought that the fish may have been avoiding turbid water in order to maintain a view of potential food items, since overall visibility and background contrast are key factors in food selection for juvenile coho salmon.

Stober, et al. (1981) determined the 96-hour LC50 of volcanic ash for coho smolts and presmolt coho. Results of the static bioassays showed 96-hour LC50 values of 18,672 mg/l and 28,184 mg/l for presmolt coho and coho smolts, respectively. Additional bioassays revealed 96-hour LC50 values for coho smolts of 2,118 mg/l and 29,580 mg/l using bentonite and mudflow, respectively.

The effects of sediment on the arctic grayling (Thymallus arcticus) have been studied, mostly with regard to placer mining sediment effects. Several studies which investigate the effects of placer mining sediments on juvenile grayling are summarized below.

McLeay, et al. (1983) studied both lethal and sublethal effects of placer mining sediment on grayling young of the year. Using recycle test tanks with a water temperature of 15°C, arctic grayling survived for 4 days in 250,000 mg/l inorganic fines and for 16 days in 50,000 mg/l inorganic fines. When the water temperature was decreased to 5°C, fish survived for 4 days in concentrations less than 10,000 mg/l. McLeay, et al. (1983) observed a 10 percent mortality (over 4 days, 5°C) in sediment concentrations of 20,000 mg/l, and a 20 percent mortality in tanks containing 100,000 mg/l sediment (4 day exposure, 5°C). The data suggest a decrease in lethal tolerance for fish acclimated to colder water, which implies a possible seasonal effect. Tests to determine 96-hour LC50 values (15°C) revealed values more than 50,000 mg/l for overburden and over 100,000 mg/l for paydirt.

Sublethal effects studies showed no effect on gill histology after 4 days exposure of grayling to 100,000 mg/l or less (McLeay, et al., 1983). However, stress tests showed increased plasma glucose values in 24-hour tests (15°C) using 50 mg/l of overburden sediment. In contrast to the results of gill histology studies by McLeay, et al. (1983), La Perriere, et al. (1983) reported that microscopic examination of gill tissue of young-of-the-year grayling showed mucus secretions with embedded sediment particles in as short as 12 hours when suspended solids were greater than 800 mg/l.

Simmons (1984) found that gill tissues of grayling appeared normal in 96-hour exposures to 170 mg/l placer mining sediments. When the concentration was increased to 1,205 mg/l, a moderate amount of gill damage was observed.

3.4.5 EFFECTS ON ADULTS

Alexander and Hansen (1983) examined the effects of the addition of sand (effective concentration of 80 ppm) on the brook trout (Salvelinus fontinalis) population of a small stream (Hunt Creek, Michigan). Adults, as well as juveniles, were collected during the stream survey. The study was conducted over a 5-year period, and showed the effects of sedimentation as well as increased suspended solids loading. Although the trout population changed gradually, a 51 percent decrease in total number of trout was observed over the 5 years.

3.5 EFFECTS OF SUSPENDED SEDIMENT ON OTHER FISH

Non-salmonid species are affected by suspended sediment in the same ways that salmonids are affected. The effects of suspended solids on primarily freshwater species will be discussed first, and will be followed by a discussion of the effects of suspended sediment on estuarine (and often anadromous) species. Both lethal and sublethal effects will be discussed together with the sediment concentrations (if known) that elicit the response.

The spawning seasons of temperate, warmwater fish are generally definable in timing and duration. The majority of warmwater riverine fish focus their reproductive activities on brief intervals during the late spring and early summer rainy season (Table 3-5). In the native state, turbid conditions occur briefly during freshets and floods, and spring rains are a stimulus for spawning. Altered watersheds have caused increases in riverine sediment loads during much of the year, and rivers carry especially heavy silt loads during the spring rainy season.

Gammon (in Sorensen, et al., 1977) published a review of the effects of suspended solids on fish. His review of material pertaining to non-salmonid fish is summarized in Table 3-6. Muncy, et al. (1979) reviewed the literature concerning the effects of suspended solids on the reproduction and early life of warmwater fish. The literature review resulted in several lists which categorized fish as tolerant or intolerant of suspended solids, and fish for which conflicting information was found. These lists are reproduced in Appendix A.

3.5.1 EFFECTS ON FRESHWATER FISH

Effects on Egg and Larval Stages

Yellow perch (*Perca flavescens*) are frequently found in freshwater lakes and rivers, but may also be found in estuarine salinities as high as 13 ppt. They are most common in clear water and numbers decrease with increasing turbidity (Krieger, et al., 1983). Suspended sediment concentrations of 100 to 500 mg/l reportedly delayed hatching of yellow perch

TABLE 3-5

Patterns of Reproductive Timing and Movement Among Warmwater Fishes.

Family	Spawning Season	Duration of Season	Movement
Petromyzontidae	Late spring	Brief	Upstream to tributaries
Acipenseridae	Early to late spring	Brief	Upstream, often extensive
Polyodontidae	Late spring	Brief	To shoal areas within large rivers
Lepisosteidae	Late spring	Brief	Inshore to weedy places
Amiidae	Late spring	Brief	Inshore to weedy places
Clupeidae	Late spring	Brief	Some anadromy
Hiodontidae	Late spring	Brief	Inshore?
Umbridae	Late spring	Brief	Limited movement to streams, ponds, marshes
Esocidae	Early to late spring	Brief	Inshore to flooded areas
Cyprinidae	Primarily early to late spring, some in summer	Brief for most, protracted for some	Upstream among fluviatile species, inshore movement among others
Catostomidae	Early to late spring	Brief	Upstream in many
Ictaluridae	Late spring to summer	Usually brief, protracted for some	None or limited inshore movement
Aphredoderidae	Early spring	Brief?	Not known
Percopsidae	Late spring	Brief	Limited upstream or inshore movement
Cyprinodontidae	Late spring to summer, perhaps year-around in some	Extended	Very limited, if any
Poeciliidae	Most warmer months?	Extended	Very limited, if any
Atherinidae	Late spring & summer	Probably brief	Not known
Gasterosteidae	Late spring & summer	Extended	None or very limited
Percichthyidae	Late spring	Brief	Inshore, some anadromy
Centrarchidae	Late spring & summer	Brief to extended	Inshore
Percidae			
Etheostomatinae	Early to late spring	Brief	To shallow water
Percinae	Early spring	Brief	To shallow water
Sciaenidae	Late spring to summer	Often lengthy	Not known

SOURCE: Muncy, et al., 1979

TABLE 3-6

Effects of Suspended Solids on Non-Salmonid Fish (Data Collected from Gammon, 1970).

Fish (Species)	Effect	Concentration of Suspended Solids	Source of Suspended Materials	Comment
Mixed fish populations	Decrease in occurence	Turbidity increase		
Mixed fish populations	Critical levels affecting populations	100-300 ppm	Industrial	England, Scotland, and Wales fisheries
Perch (*Perca flavesiens*)	High egg mortality	(Silting)		
European Pike Perch (*Lucioperca lucioperca*)	High egg mortality	(Silting)		
Zebra (*Brachyolanio rerior*)	Earlier egg hatch and no increase in egg mortality	18,000-30,000 ppm	Limestone dust	Fry died within 4 hours at 74,800
Barbel (*Barbus fluviatilis*)	Decreased migration	(Increasing turbidity)		
European eel (*Anguilla anguilla*)	Increased migration	(Increasing turbidity)		
Smallmouth bass (*Micropterus dolomieui*)	Successful nesting, spawning, hatching	(Sporadic periods of high turbidity)		

SOURCE: Sorensen, et al., 1977.

eggs by 6 to 12 hours (Wang and Tatham, in Muncy, et al., 1979). Mortalities of yellow perch larvae were significant at sediment concentrations of 500 mg/l and 1,000 mg/l (Auld and Schubel, in Muncy, et al., 1979).

Turbid water (250-2,350 JTU) caused a loss of orientation in smallmouth bass fry. Larimore (in Muncy, et al., 1979) stated that losses of smallmouth bass fry during floods could be caused by simultaneous rapid changes in turbidity, light, velocity, and turbulence.

Effects on Juveniles

Heimstra, et al. (in Muncy, et al., 1979) reported that the movement activity of juvenile largemouth bass was reduced in turbidities of 14-16 JTU for 30 days. Bass in turbid water also showed a high incidence of "coughing," a reaction which helps fish cope with limited amounts of sediment deposition on the gills.

Effects on Adults

The feeding rates of bluegill (Lepomis macrochirus) are decreased in turbid water (Gardner, 1981). The fish were acclimated to the turbid water for 24 hours before being fed for a period of 3 minutes. The feeding rates of bluegill were calculated for three turbidity levels (60, 120 and 190 NTU) and in clear water (control). Fish in clear pools ate an average of 41 prey each in a 3-minute period, while fish in the highest turbidity ate 22 prey per fish. Bluegill feeding rates declined from about 14 prey per minute in the control to 11, 10 and 7 per minute in pools of 60, 120, and 190 NTU, respectively. Vinyard and O'Brien (in Muncy, et al., 1979) noted that turbidities as low as 30 NTU reduce the reaction distances of bluegill for all prey sizes.

Production of largemouth bass (Micropterus salmoides), bluegill (Lepomis macrochirus), and redear sunfish (Lepomis microlophus) was lower in turbid ponds than in clear ponds. Buck (in Rosenberg and Snow, 1975) found that production in clear (less than 25 mg/l) ponds was 180.9 kg/ha, while production in intermediately turbid (25-100 mg/l) and turbid (more than 100 mg/l) waters averaged 105.3 kg/ha and 32.8 kg/ha.

Wallen (in Sorensen, et al., 1977) tested the reactions of several warmwater fish to turbidity. He found that most of the experimental fish survived more than 100,000 ppm turbidity for a week or longer, but these same fish died at turbidities of 175,000 to 225,000 ppm. Lethal turbidities caused death in 15 minutes to 2 hours of exposure. Some effects on selected fish used in Wallen's study are listed in Table 3-7.

3.5.2 EFFECTS ON ESTUARINE FISH

The reproductive cycles of many of the estuarine fish are such that they migrate up freshwater streams to spawn during the late spring and early summer. This is generally the period of high flow, which is accompanied by increased turbidities and high sediment loads.

Several publications contain information about sediment effects on several estuarine species. Muncy, et al. (1979) reviewed the literature pertaining to the effects of suspended sediment on warmwater species, including those estuarine species whose reproductive strategies are to spawn in freshwater or nearly freshwater areas. O'Connor, et al. (1976, 1977) investigated both lethal and sublethal responses of several estuarine species to suspended solids, some of which will be included in the following section.

Effects on Egg Stage

Striped bass (Morone saxatilis) migrate to fresh or nearly freshwater to spawn. Spawning may begin in mid-February in the southern portion of the striped bass range, whereas in the extreme northern portions of the range, spawning may not begin until June or July (Bain and Bain, 1982). Suspended solids concentrations of 100 to 500 mg/l delayed hatching of striped bass eggs by 4 to 6 hours (Wang and Tatham, in Muncy, et al., 1979). Morgan, et al. (1983) reported significant developmental delays at sediment loads of 800 mg/l or more, and concentrations of 2,000 mg/l caused developmental delays of 12 to 15 hours.

A suspended sediment concentration of 5,250 mg/l delayed hatching of white perch (Morone americana) eggs by 24 hours (Morgan, et al., 1983). Concentrations as low as 100 to 500 mg/l caused a 4 to 6 hour delay (Wang and Tatham, in Muncy, et al., 1979).

TABLE 3-7

Some Effects of Turbidity on Selected Fish Species (Data from Wallen, 1951)

Species	Turbidity at First Adverse Reaction	Turbidity at First Death
Golden Shinner (Notemigonus crysoleucas)	20-50,000 ppm	50-100,000 ppm
Mosquitofish (Gambusia affins)	40,000	80-150,000
Goldfish (Carassius auratus)	20,000	90-120,000
Carp (Cyrinus carpio)	20,000	175-250,000
Red Shinner (Notropis lutrensis)	100,000	175-190,000
Largemouth Black Bass (Micropterus salmoides)	20,000	101,000 (average)

SOURCE: Sorensen, et al., 1977.

Effects on Larval Stage

Auld and Schubel (in Muncy, et al., 1979) reported significant mortalities of striped bass larvae in suspended sediment concentrations of 500 mg/l and 1,000 mg/l. Morgan, et al. (1983) determined a 24-hour LC50 of 20,417 mg/l sediment, and a 96-hour LC50 of 6,292 mg/l for larval striped bass. Fifty percent of the white perch larvae reportedly survived sediment concentrations of 67,000 mg/l for 24 hours (24-hour LC50 = 67,000 mg/l), while the 48-hour LC50 was found to be 6,900 mg/l.

Effects on Juveniles and Adults

O'Connor, et al. (1976) tested the responses of several estuarine species to various suspended sediment concentrations. Fish that were tested were collected from the Patuxent River estuary, Maryland. The life stages of the fish being exposed to the sediment concentrations were not specified for many of the species tested. Thus, the results of these studies will be presented as effects on juveniles and adults.

O'Connor, et al. (1976, 1977) studied the effects of suspended sediment on spot (*Leiostomus xanthurus*), an estuarine-dependent species that lives in the estuary during its juvenile period. Static bioassays yielded the following 24-hour lethal concentrations for fuller's earth and natural sediment (from the Patuxent River, Maryland):

Sediment	LC (g/l)		
	LC10	LC50	LC90
Fuller's earth	13.08	20.34	31.62
Natural sediment	68.75	88.00	112.63

Increasing duration of exposure times caused an overall reduction of LC10, LC50 and LC90. These values are shown in Table 3-8. Exposure to the sublethal concentration of 1.27 g/l fuller's earth for 5 days did not result in significant changes in the hematological parameters that were measured (hematocrit, hemoglobin concentration, blood cell count).

TABLE 3-8

LC10, LC50 AND LC90 Values for Spot, With Increasing Duration of Exposure to Fuller's Earth

Duration of Bioassay (h)	LC10	LC50	LC90
12	27.56	42.36	65.12
18	21.07	33.06	51.87
20	-----[a]	-----	-----
24	13.08	20.34	31.62
48	1.13	1.90	3.17

[a] Not tested.

SOURCE: O'Connor, et al., 1976.

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White perch exposed to fuller's earth for various times showed a reduction of LC10, LC50 and LC90, with increasing duration (Table 3-9). Lethal concentrations of fuller's earth and natural sediments were determined for 24-hour exposures (O'Connor, et al., 1976). The results were:

Sediment	LC (g/l)		
	LC10	LC50	LC90
Fuller's earth	3.05	9.85	31.81
Natural sediment	9.97	19.80	39.40

Particle size and shape probably caused the variation in the lethal effect to species (O'Connor, et al., 1976). The influence of particle size has been discussed previously in the Introduction to this chapter.

O'Connor, et al. (1977) studied the sublethal effects of suspended sediment on white perch. Adult fish were exposed to 0.65 g/l fuller's earth for 5 days. Fish exposed to sublethal concentrations of suspended solids showed the same hematological responses as fish deprived of sufficient oxygen. White perch showed significant increases in red blood cell count, hemoglobin concentration and microhematocrit. Examination of the gill tissues of exposed white perch revealed many mucus cells on the gills and swelling of the secondary lamellae.

Several other estuarine species were tested in bioassays using fuller's earth. The results of these tests, which determined lethal concentrations, are summarized in Tables 3-10 and 3-11. Both menhaden and bluefish exhibited 100 percent mortality at relatively low concentrations (1.2 g/l and 0.8 g/l, respectively) of fuller's earth (Table 3-10). The LC10, LC50, and LC90 for fuller's earth were calculated for bay anchovy, Atlantic silverside, mummichog and striped killifish (Table 3-11). Of these fish, the bay anchovy and Atlantic silverside were the most sensitive to suspended fuller's earth.

TABLE 3-9

LC10, LC50 and LC90 Values for White Perch, with Increasing Duration of Exposure to Fuller's Earth

Duration of Bioassay (h)	LC10	LC50	LC90
12	32.07	41.00	52.41
18	-----[a]	-----	-----
20	7.91	14.99	28.38
24	3.05	9.85	31.81
48	0.67	2.96	13.06

[a] Not tested.

SOURCE: O'Connor, et al., 1976.

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TABLE 3-10

Lowest Fuller's Earth Concentration Causing 100-Percent Mortality in a 24-Hour Exposure for Five Estuarine Fish

Species	Age Class	Individuals (No.)	Test Conditions		
			Salinity (ppt)	Temp. (°C)	Concentration fuller's earth (g/l)
Menhaden	0+	30	5.5	25±2	1.2
Menhaden	1+	60	23.6	22±2	0.8
Bluefish	1+	26	20.0	22±2	0.8
Weakfish	0+	47	20.0	22±2	6.8
Weakfish	0+	20	5.5	25±2	8.2
Striped Bass	2+	31	5.5	25±2	16.6
Croaker	1+	17	5.5	25±2	11.4

SOURCE: O'Connor, et al., 1976

276/6

TABLE 3-11

LC10, LC50, AND LC90 Values Determined for 24-Hour Exposure of Estuarine Fish

Species	Lethal LC10	Concentration (g/l fuller's earth) LC50	LC90
Bay anchovy	2.31	4.71	9.60
Atlantic silverside	0.57	2.40	10.00
Mummichog	24.47	39.00	62.17
Striped killifish	23.77	38.18	61.36

SOURCE: O'Connor, et al., 1976

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O'Connor, et al. (1976) classified several estuarine fish species according to their toleration of suspended solids. The groups were:

1. Class I: Suspension-Tolerant Species. The concentration of fuller's earth required to attain the 24-hour LC10 value is equal to or in excess of 10 g/l. Tolerant species were the mummichog, striped killifish, and spot.

2. Class II: Suspension-Sensitive Species. LC10 values for 24-hour exposure to fuller's earth were between 1 and 10 g/l. The sensitive species were white perch, bay anchovy, juvenile menhaden, striped bass, croaker, and weakfish.

3. Class III: Highly Sensitive Species. Twenty-four-hour LC10 values were less than or equal to 1 g/l of fuller's earth. Highly sensitive species were Atlantic silverside (24-hour LC10 value 0.57 g/l), juvenile bluefish, juvenile menhaden and young of the year white perch. Juvenile bluefish and juvenile menhaden failed to survive in concentrations of 0.8 g/l for more than 18 hours. Young-of-the-year white perch suffered 100 percent mortality in 0.75 g/l fuller's earth in 20 hours.

4.0 A FRAMEWORK FOR SUSPENDED SEDIMENT CRITERIA TO PROTECT AQUATIC LIFE

4.1 INTRODUCTION

As shown in Chapter 2, cultural, geologic and meteorologic factors influence suspended sediment concentrations in a water body. A cause and effect interplay exists between geology, climate, and hydrology, which influence topography, soil cover, and land use. Regions of similar geology exposed to similar climate and meteorology for equal amounts of time will display similar patterns of hydrologic response and sedimentation.

Aquatic life cycles may be related to temperature and hydrologic conditions. A national single level criterion for suspended solids may not be appropriate due to regional and seasonal variations in aquatic life and in naturally occuring sedimentation processes. Regional and seasonal criteria should be considered that are based on a consistent methodology and unit of measure. Incorporation of region and season into criteria ultimately will require a detailed understanding of hydrology, of how the normal life cycle of the resident biota proceeds in concert with hydrologic phenomena, and of how the 'toxicity' expressed by suspended sediment is governed by hydrologic phenomena.

The concept of identifying hydrologically similar basins based on relationships between landform characteristics and the controlling factors of climate, geology, and vegetation is not novel. Quantitative geomorphology was revolutionized in 1945 when Horton (1945) introduced his system of stream ordering and laws of drainage composition. Horton's work was supplemented by Langbein (1947), Strahler (1957), Smart (1972) and others.

Important considerations in defining regions for suspended sediment criteria should include (1) physiographic province; (2) annual rainfall distribution; (3) climate; (4) watershed boundaries as indicators of hydrologically controlled ecosystems; and (5) political jurisdictions in which a suspended solids criteria is implemented and enforced. The following sections present possible approaches for regional and seasonal delineation.

4.2 REGIONAL BASES FOR CRITERIA

4.2.1 APPROACHES

Several approaches to regionalization are discussed below. These approaches include physiographic province, principal drainage basin, land resources, climate and hydrology, ecoregion, and political jurisdiction.

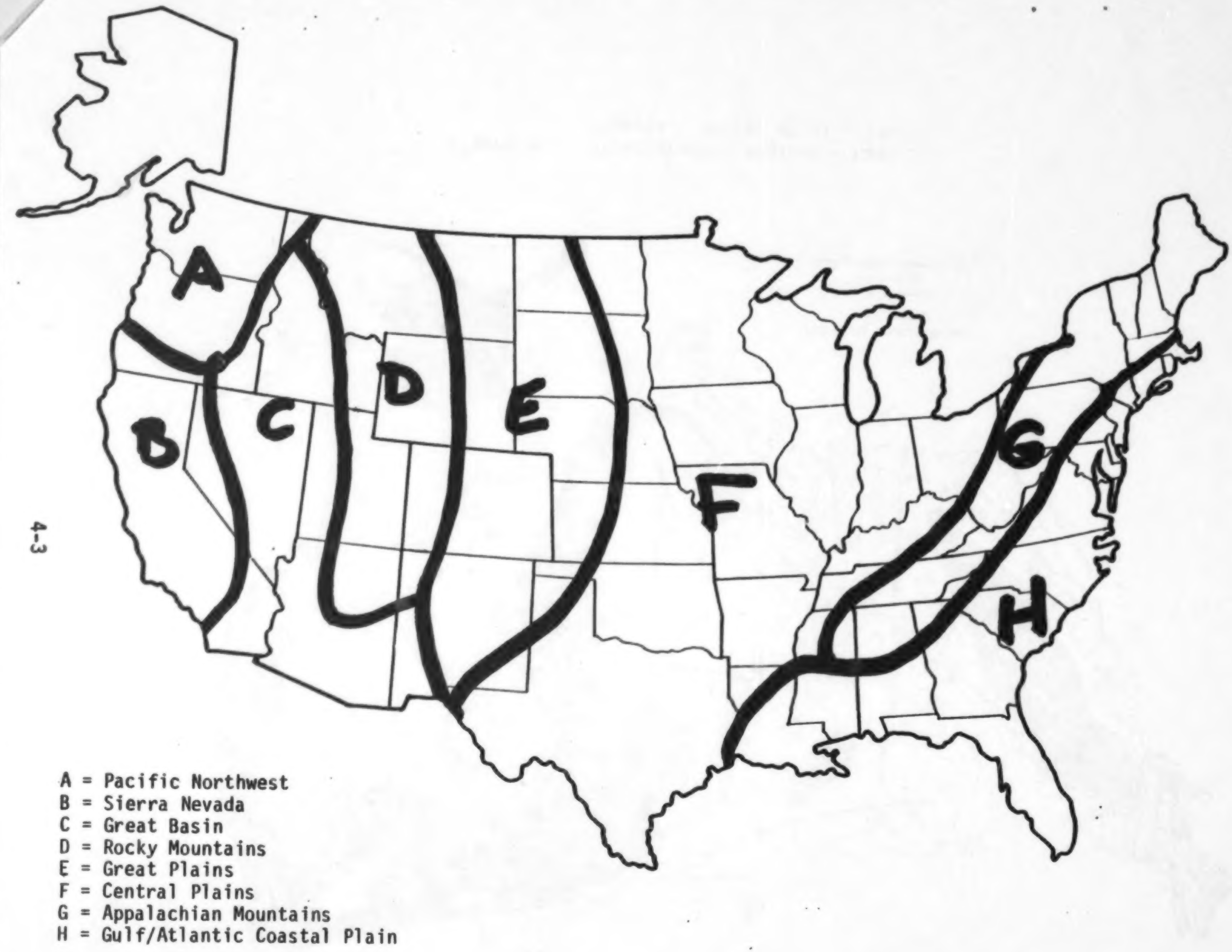
4.2.2 REGIONALIZATION BY PHYSIOGRAPHIC PROVINCE

The identification of regions by physiography is based on physical description and geologic characteristics. Advantages include the ability to address isolated areas of geomorphic similarity for sedimentation and the ability to distinguish aquatic life habitats, as in coastal plain versus Piedmont variations. Disadvantages are mainly due to the degree or number of physiographic regions to establish and the lack of precision in defining regional boundaries. An example of a general classification by broad physiography is shown in Figure 4-1. A more distinct classification is shown in Figure 4-2.

4.2.3 REGIONALIZATION BY PRINCIPAL DRAINAGE BASIN

Regionalization by principal drainage basin allows delineation of isolated ecosystems. Contributing sources of runoff and pollution from tributaries can be easily monitored and controlled. Watershed management can be applied for optimum multi-purpose water resources planning. Disadvantages result from physiographic variance within major drainage basins. Figure 4-3 illustrates an example of regionalization by major drainage basin.

The Office of Water Data Coordination (OWDC) was established within the U.S. Geological Survey to coordinate water data acquisition and distribution after the United States Bureau of the Budget Circular A-67 was issued in 1964 (U.S. Geological Survey, 1970). OWDC divided the conterminous United States into 79 principal geographic units (Figure 4-4). The units, divided by drainage basin, can be used to provide a basis for regionalization in establishing suspended solids criteria that can be integrated with the national network of data acquisition.



A = Pacific Northwest
B = Sierra Nevada
C = Great Basin
D = Rocky Mountains
E = Great Plains
F = Central Plains
G = Appalachian Mountains
H = Gulf/Atlantic Coastal Plain

Figure 4-1. Physiographic Regions, Case 1

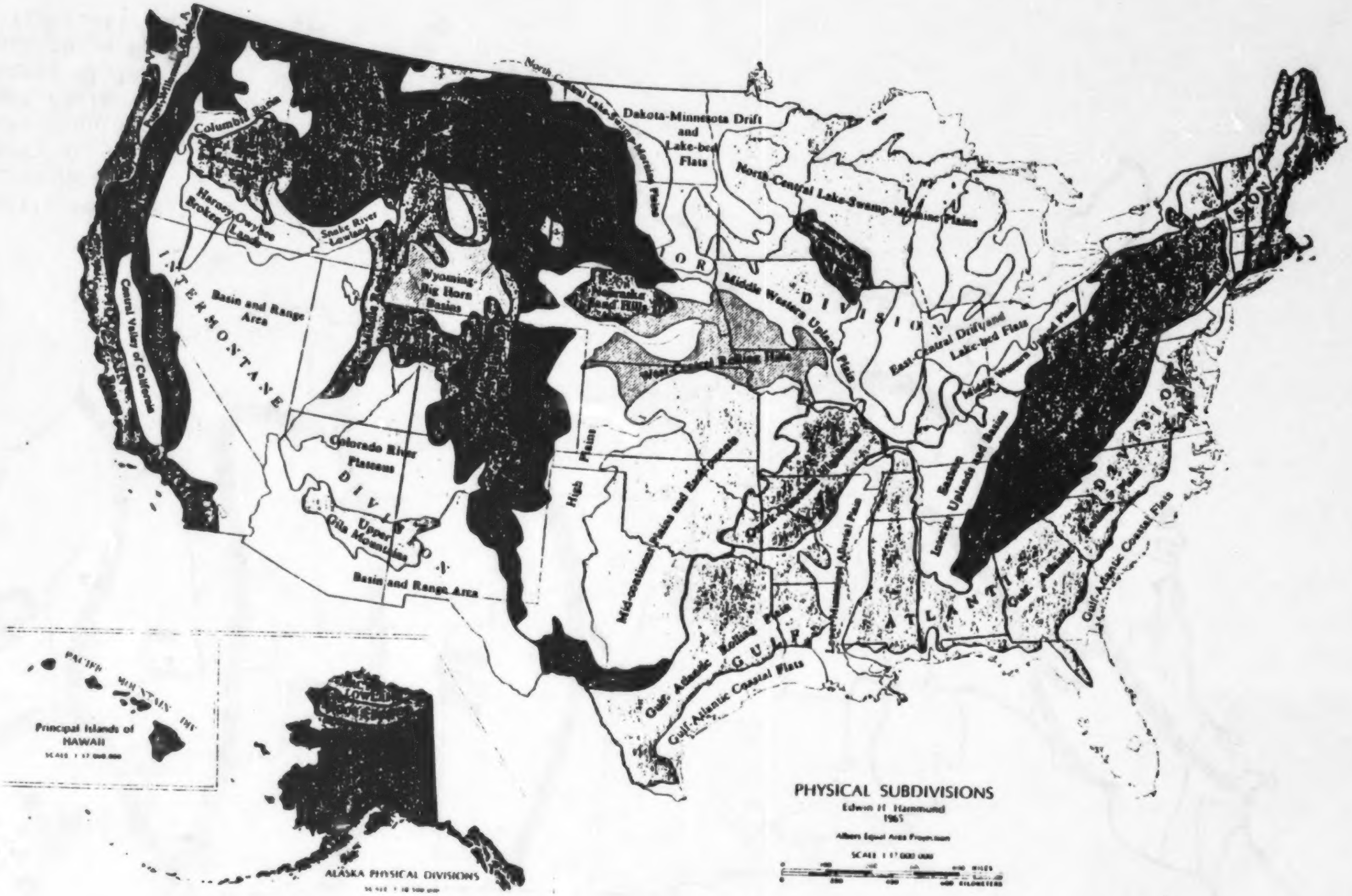

Columbia Basin
Harney-Owyhee Broken Lands
Snake River Lowland
INTERMONTANE
Basin and Range Area
Central Valley of California
Wyoming Big Horn Basin
Colorado River Plateaus
Upper Gila Mountains
Basin and Range Area
Dakota-Minnesota Drift and Lake-bed Flats
North-Central Lake-Swamp-Moraine Plains
Middle Western Upland Plain
East-Central Drift and Lake-bed Flats
Interior Uplands and Basins
High Plains
Mid-continent Plains and Escarpments
Gulf-Atlantic Rolling Plain
Gulf-Atlantic Coastal Flats
GULF
ATLANTIC
DIVISION
Principal Islands of HAWAII
ALASKA PHYSICAL DIVISIONS
PHYSICAL SUBDIVISIONS
Edwin H. Hammond
1965
Albers Equal Area Projection

Figure 4-2. Physiographic Regions - Case 2
(Source: Miller et al., 1962)

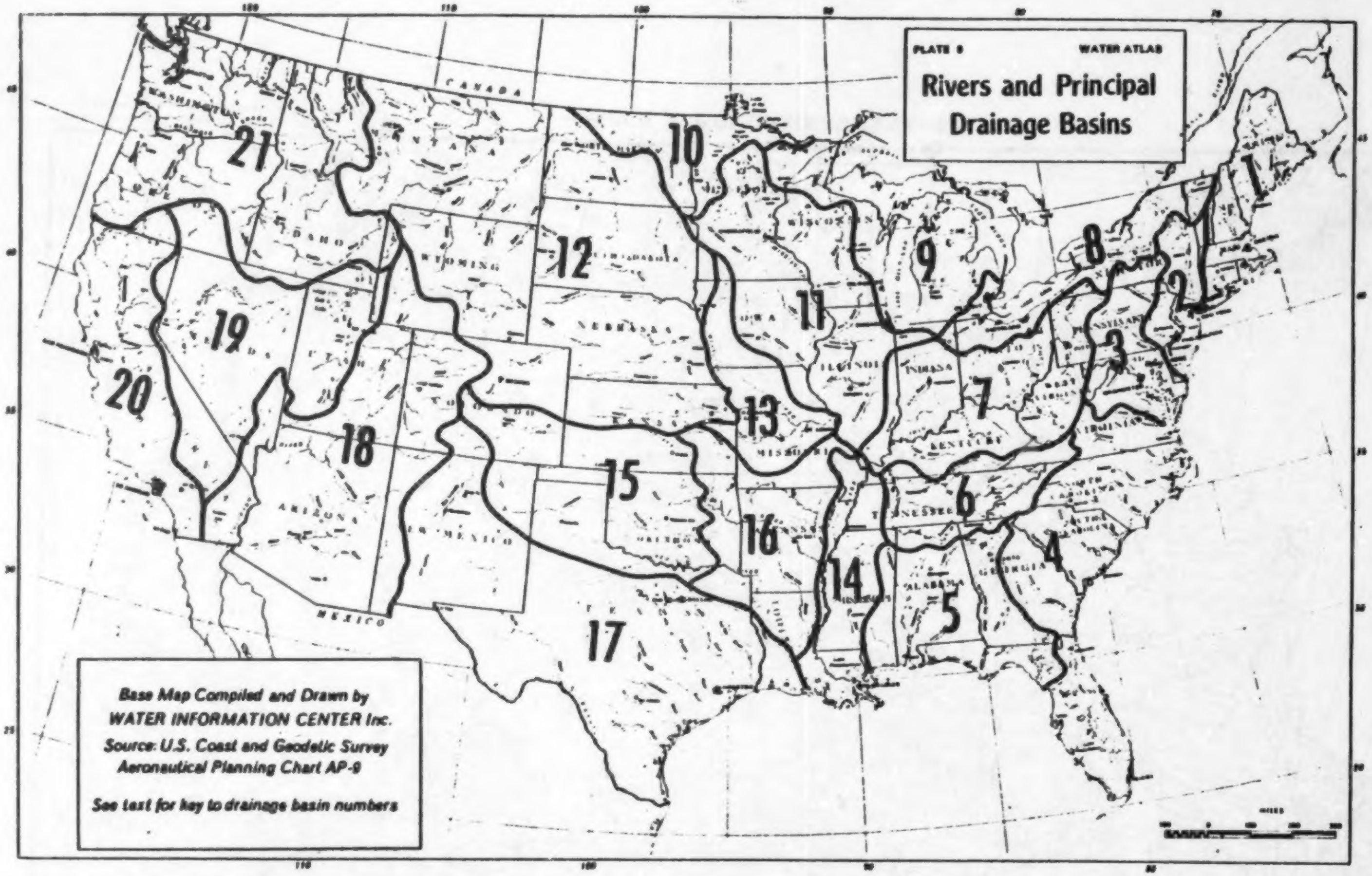


PLATE 9
WATER ATLAS
Rivers and Principal Drainage Basins
Base Map Compiled and Drawn by
WATER INFORMATION CENTER Inc.
Source: U.S. Coast and Geodetic Survey
Aeronautical Planning Chart AP-9
See text for key to drainage basin numbers
CANADA
MEXICO
WASHINGTON
IDAHO
WYOMING
NEBRASKA
IOWA
ILLINOIS
INDIANA
KENTUCKY
TENNESSEE
ALABAMA
GEORGIA
ARIZONA
NEW MEXICO
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Figure 4-3. Regionalization by Principal Drainage Basin
(Source: Miller et al., 1962)

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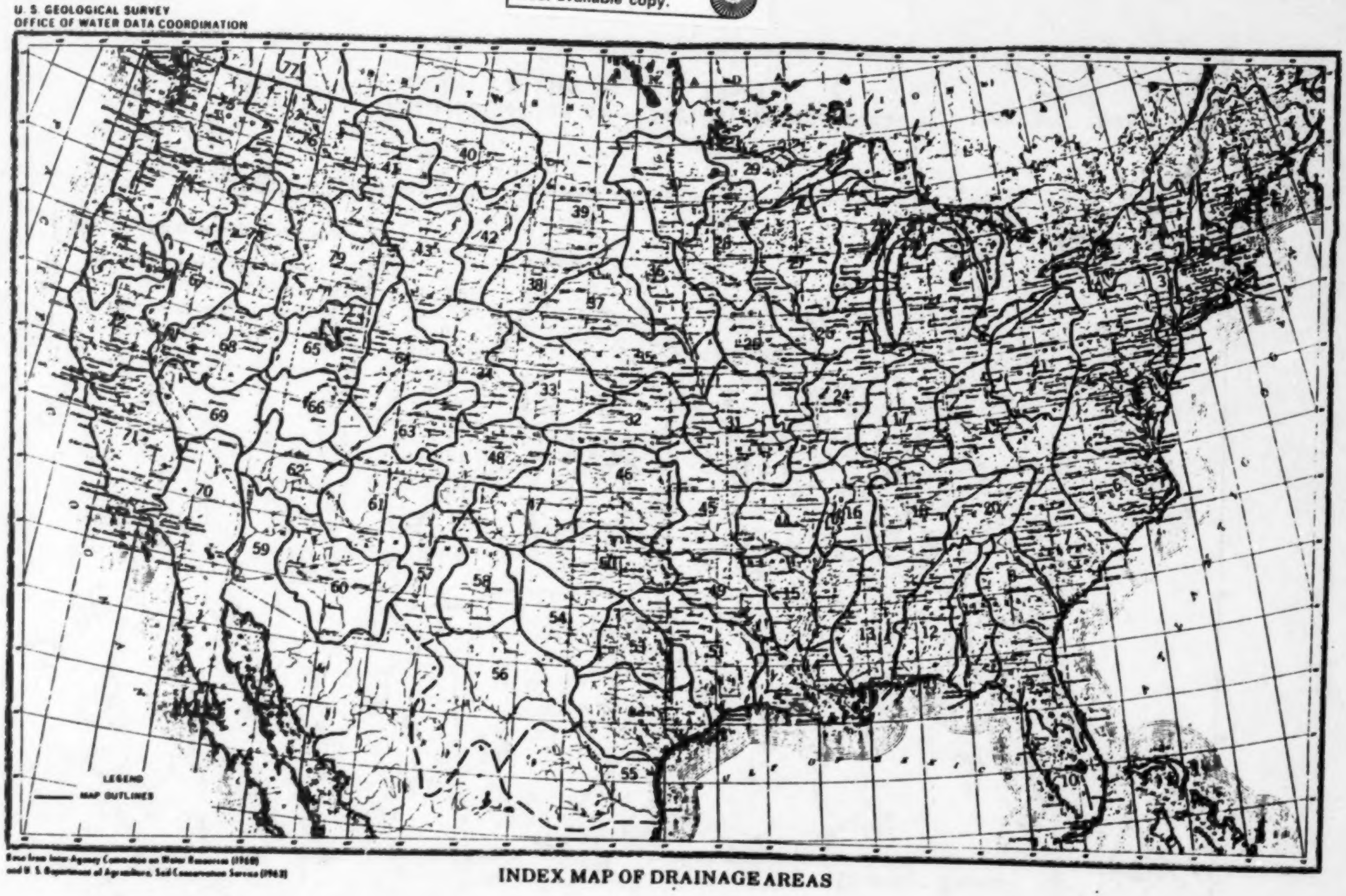
U. S. GEOLOGICAL SURVEY
OFFICE OF WATER DATA COORDINATION
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15
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10
LEGEND
MAP OUTLINES
INDEX MAP OF DRAINAGE AREAS

Base from Inter-Agency Committee on Water Resources (1969)
and U. S. Department of Agriculture, Soil Conservation Service (1963)

Figure 4-4. Office of Water Data Coordination, Map of Drainage Basins (Source: USGS, 1970)

4.2.4 REGIONALIZATION BY LAND RESOURCES

The Soil Conservation Service (SCS) of the U.S. Department of Agriculture (USDA) produced an atlas containing 20 land resources regions encompassing broad patterns of soils, climate, natural vegetation, water resources, topography, and land use (Soil Conservation Service, 1963). The emphasis for establishing the regions was based on combinations and intensities of problems in soil and water conservation. The distribution of the regions is given in Figure 4-5 and descriptions of each can be found in Appendix B.

4.2.5 REGIONALIZATION BY CLIMATE AND HYDROLOGY

Difficulties exist in trying to establish regionalization based on climate and hydrology due to the dynamic nature of each. The Water Atlas of the United States (Miller et al., 1962), Climatic Atlas of the United States (Environmental Science Services Adminstration, 1968), and Technical Paper 40 (Weather Bureau, 1963) provide national distributions of climatic data including precipitation, normal daily temperatures, evaporation, sunshine, solar radiation, and wind characteristics. Average daily and annual values of these records can be used as a guide for establishing regions based on climate. Characteristics that can be used as guidelines include average precipitation (Figure 4-6), runoff (Figure 4-7), number of days with thunderstorms (Figure 4-8), and seasonal patterns of runoff which can be used as a basis for seasonal identification as discussed in the following section.

4.2.6 AQUATIC ECOREGIONS

Studies conducted at the EPA Environmental Research Laboratory in Corvallis, Oregon, have focused on the 'aquatic ecoregion,' in which least disturbed streams provide examples of the best chemical, physical, and biological conditions that can be expected in a given ecoregion. An aquatic ecoregion is defined primarily on the basis of topography, soil type, vegetation, and land use.

Water quality objectives for background and uncontrollable anthropogenic suspended sediment, based on these studies, would provide some controls on settled sediment as well. Where appropriate, these studies might provide a

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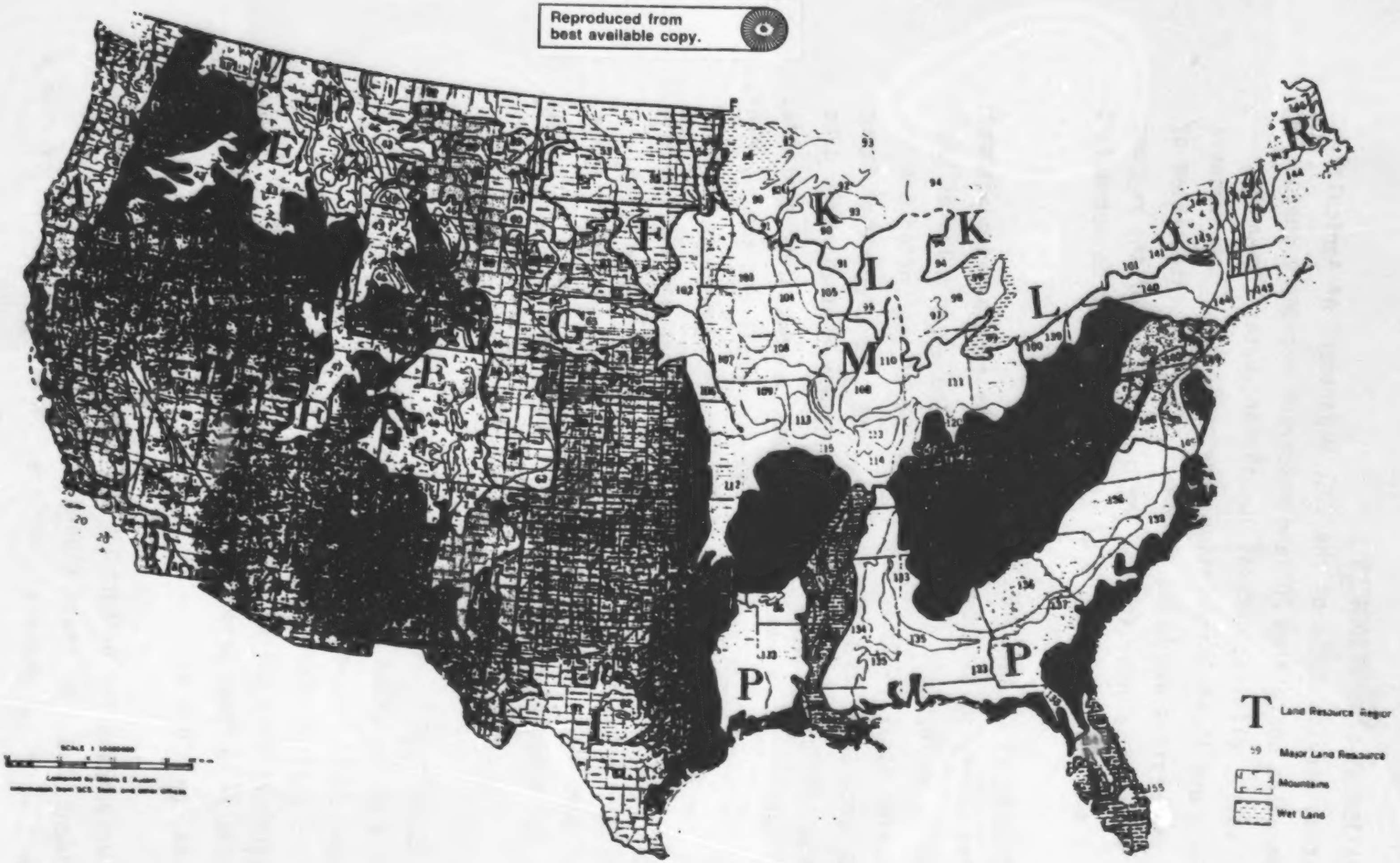
E
F
G
E
F
K
K
L
L
M
P
P
R
T Land Resource Region
59 Major Land Resource
Mountains
Wet Land

Figure 4-5. Regionalization by SCS Land Resource Units. (Source: Soil Conservation Service, 1963)

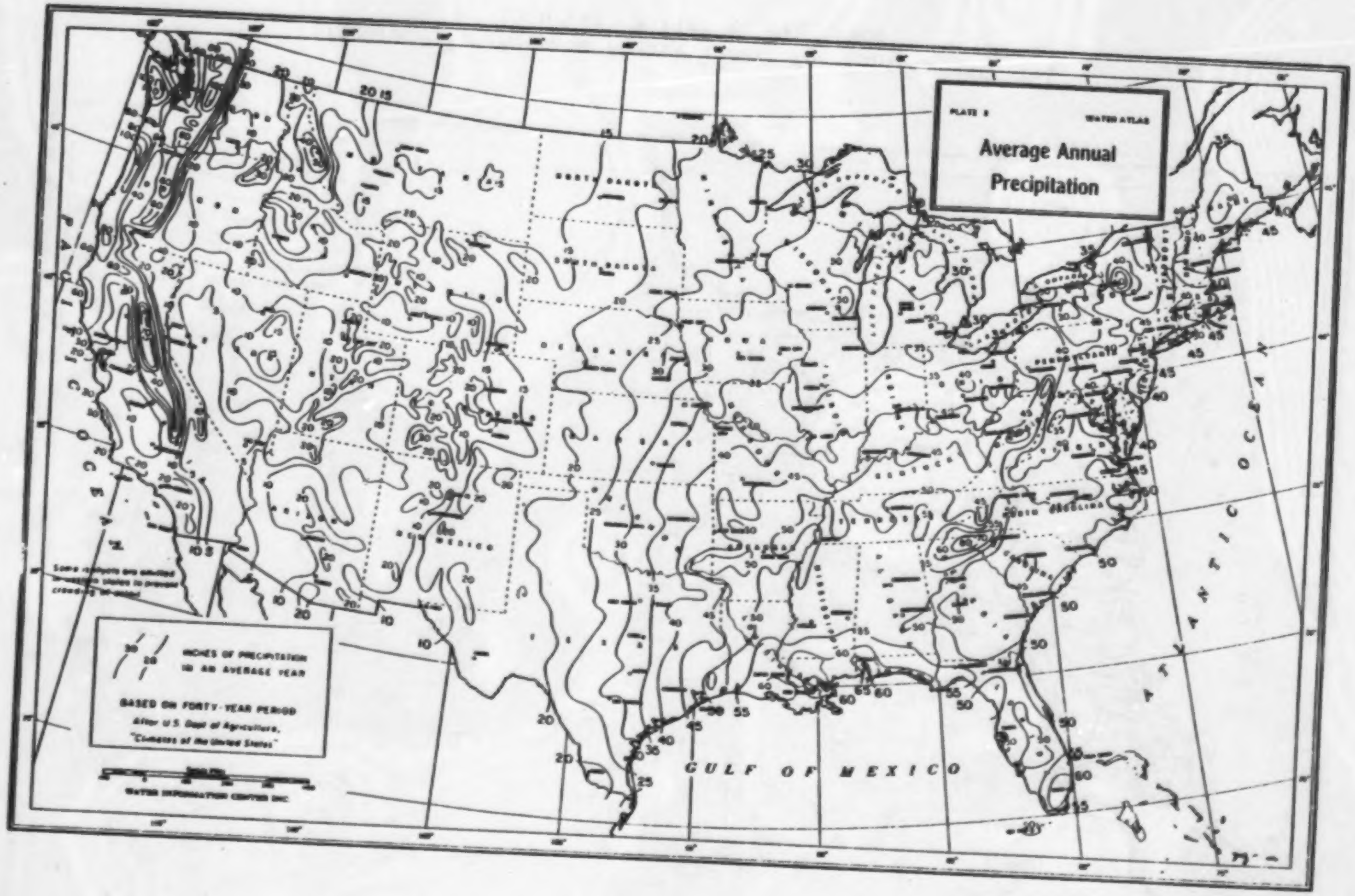
PLATE 8
WATER ATLAS
Average Annual Precipitation
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
INCHES OF PRECIPITATION IN AN AVERAGE YEAR
BASED ON FORTY-YEAR PERIOD
After U.S. Dept of Agriculture, "Climates of the United States"
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Figure 4-6. Average Annual Precipitation for Conterminous U.S. (Source: Miller et al., 1962)

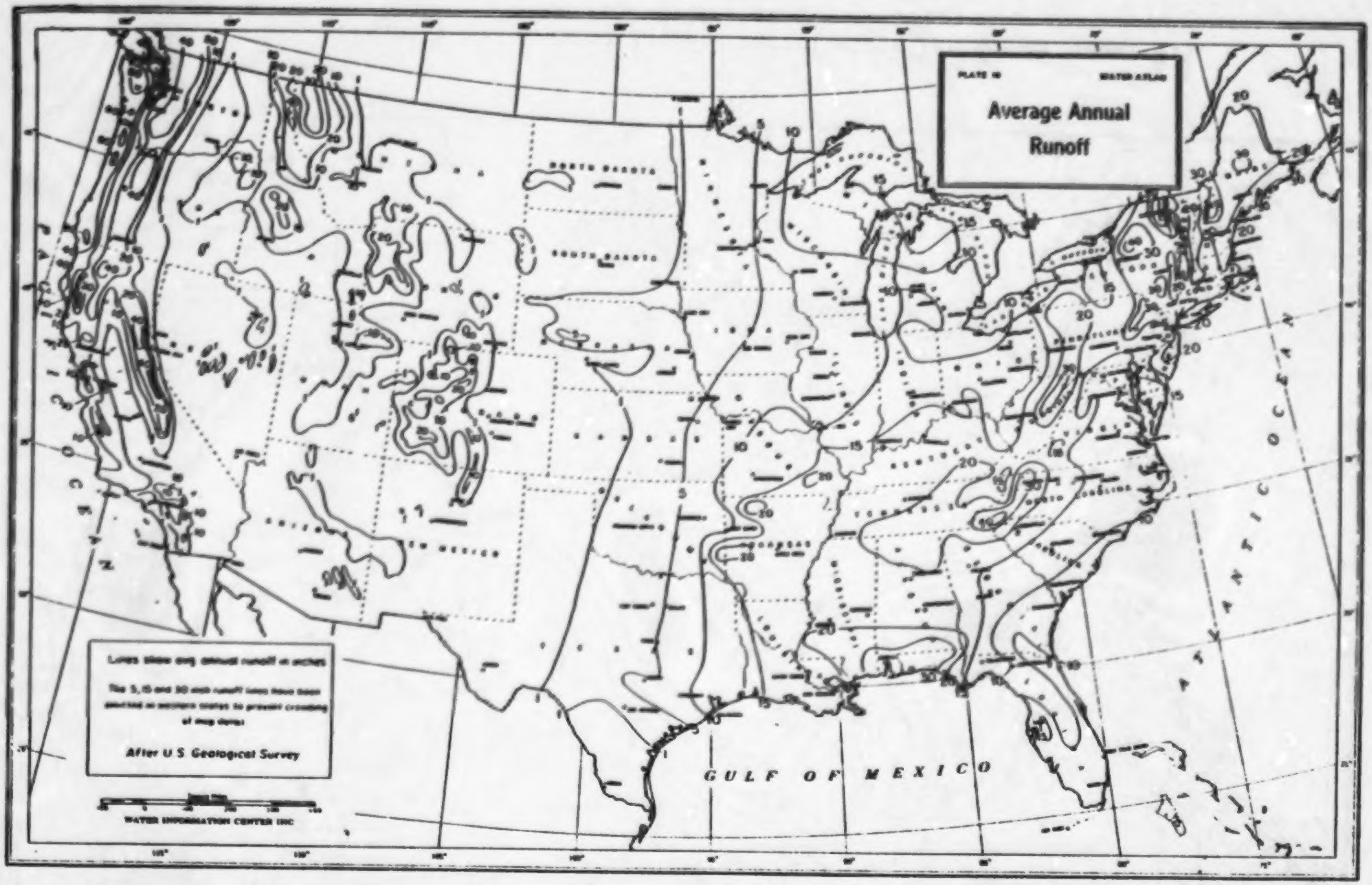
WATER ATLAS
Average Annual Runoff
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEW MEXICO
Lines show avg annual runoff in inches
The 5, 15 and 30 inch runoff lines have been omitted in eastern states to prevent crowding of map detail
After U S Geological Survey
WATER INFORMATION CENTER INC

Figure 4-7. Average Annual Runoff for Conterminous U.S. (Source: Miller et al., 1962)

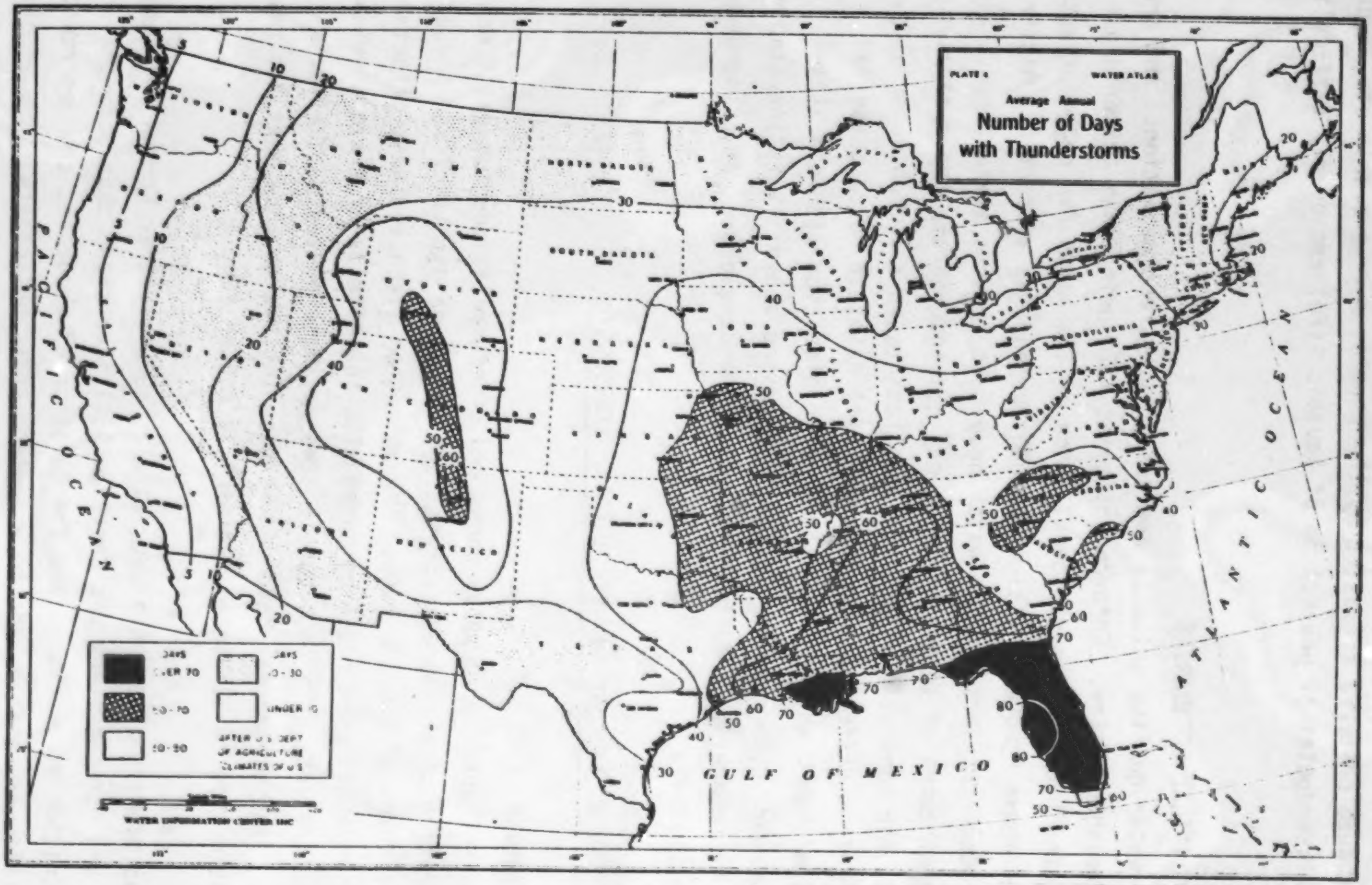
PLATE 4
WATER ATLAS
Average Annual
Number of Days
with Thunderstorms
NORTH DAKOTA
SOUTH DAKOTA
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
5
10
20
30
40
50
60
70
80
DAYS
OVER 70
50 - 70
30 - 50
DAYS
10 - 30
UNDER 10
AFTER U.S. DEPT
OF AGRICULTURE
CLIMATES OF U.S
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Figure 4-8. Average Annual Number of Days With Thunderstorms, for Conterminous U.S. (Source: Miller et al., 1962)

good starting point for the establishment of criteria for suspended sediment, although criteria suggested by the studies may be overly stringent (from the standpoint of protection of aquatic life) and overly difficult to attain.

4.2.7 POLITICAL BOUNDARIES

National water quality criteria are essentially recommendations, and are not enforceable by law. Enforcement comes into being when criteria are incorporated into a state standard. Each of the bases for regionalization discussed above ignores political boundaries and, as a practical matter, may not adequately address the water body that crosses state lines. Given that the statutes of adjacent states may not incorporate the same uses or standards for conventional and toxic pollutants in a common water body, it is likely that differences in approach will maintain for a suspended sediment standard as well. Although regionalization within a state should be encouraged, using one of the bases discussed above, it is inevitable that state boundaries will be a factor in the development of suspended sediment criteria.

4.3 COMBINING BIOLOGY AND STATISTICAL HYDROLOGY

4.3.1 INTRODUCTION

As seen in Chapter 3, complex cause and effect relationships exist between concentration of suspended sediment and impact on specific life stages of specific forms of aquatic life. The attention given sediment effects on aquatic life has been small compared with the effects of toxic chemicals on aquatic life and, as a consequence, the database on sediment effects is sparse. Size of the database notwithstanding, we do know that the response of aquatic life to suspended sediment is rather complex.

Previous studies of ammonia (Wu, et al., 1982), copper (Brown and Wang, 1984), and cadmium (Wang and Carter, 1984) have shown that both the concentration of exposure, and the duration of exposure, are important to the ability of aquatic life to withstand toxic pollutants. The information in Chapter 3 suggests that the same is true for suspended sediment. In the remainder of Chapter 4, we will discuss, on a hypothetical basis, the tie between hydrologic events and the duration-concentration response of aquatic life, and combine the two phenomena into a procedure for the establishment of criteria for suspended sediment. Since sediment levels in a stream are strongly related to seasonal rainfall and streamflow (Chapter 1), hydrology provides a good starting point for the formulation of criteria.

4.3.2 SEASONAL GENERATION OF SUSPENDED SEDIMENT

Because rainfall and streamflow follow seasonal patterns, suspended sediment concentrations in a stream follow seasonal patterns. The fact of seasonality argues strongly for seasonal criteria.

One approach to establishing criteria within regions is by calendar season. A disadvantage to the calendar definition is that hydrologic seasons and stages in the life cycle do not necessarily coincide with calendar seasons. Seasons might better be defined as portions of the water year (October through September), where distinctions such as rainy season and dry season would be more conducive to analysis than an analysis by calendar season. Seasons based on trends in the water year could be region or even site specific and would present a logical framework for blending hydrology and toxicity into water quality criteria for suspended sediment.

Defining criteria by month would provide even finer resolution to accommodate temporal variations in hydrology and life cycle. However, the existing database on biological effects is not large enough to support this degree of refinement, and the specification of monthly criteria would prove to be complex, cumbersome, unwieldy, and unnecessary.

4.3.3 HYDROLOGY

Since rainfall and runoff are the dynamic governing agents in the production of sediment and high suspended solids concentrations, it is logical to base criteria on seasonal patterns of runoff. Figures 4-9, 4-10, and 4-11 illustrate temporal variations in runoff across the country.

The type of information presented in Figure 4-9 is generated at numerous river gages maintained by various state agencies and by the U.S. Geological

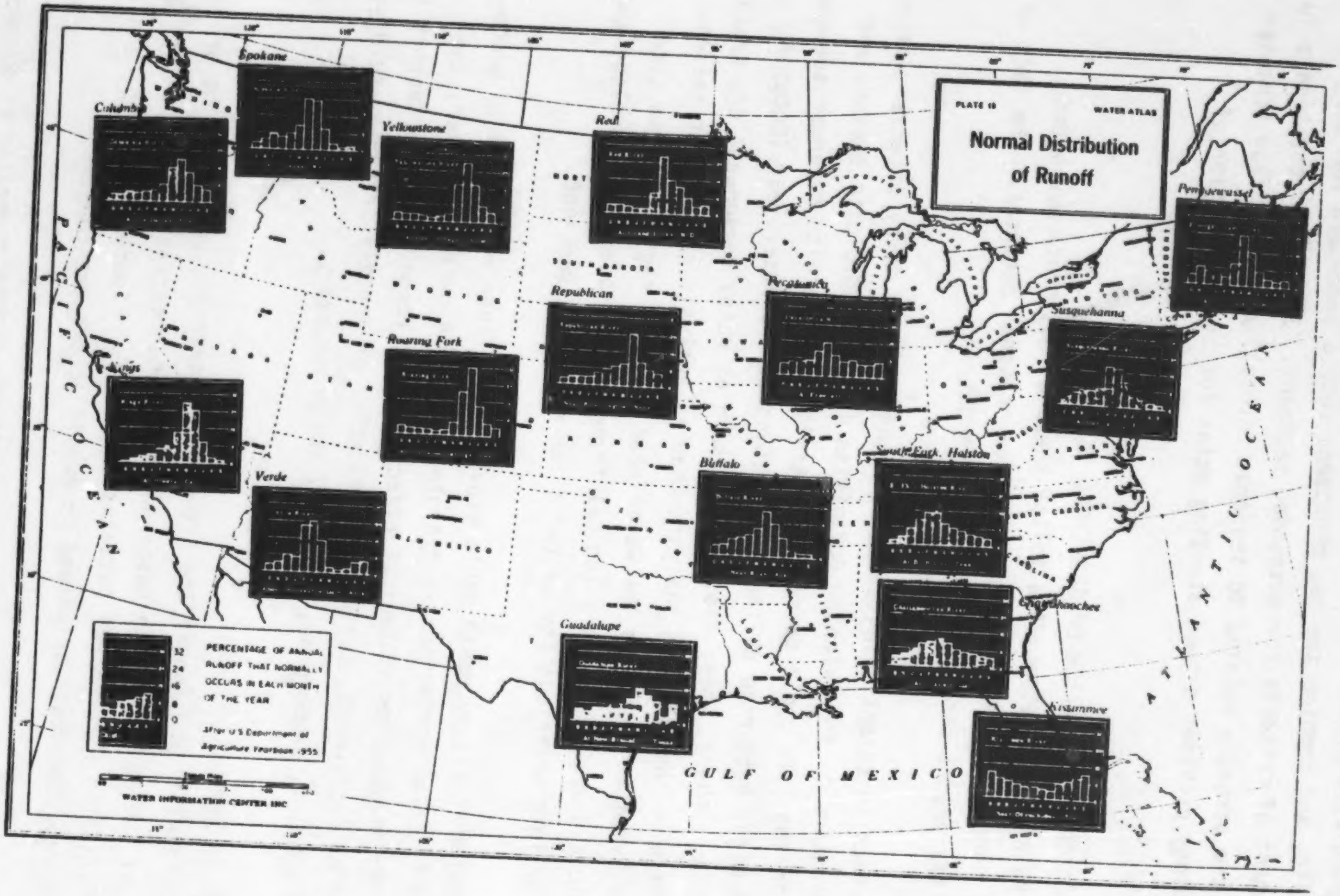
PLATE 10
WATER ATLAS
Normal Distribution
of Runoff
Columbia
Spokane
Yellowstone
Red
Pemigewasset
Republican
Roaring Fork
Kings
Verde
Buffalo
South Fork, Holston
Susquehanna
Chattahoochee
Guadalupe
Kissimmee
SOUTH DAKOTA
NEW MEXICO
ONTARIO
NORTH CAROLINA
PACIFIC OCEAN
GULF OF MEXICO
ATLANTIC OCEAN
32
24
16
8
0
PERCENTAGE OF ANNUAL RUNOFF THAT NORMALLY OCCURS IN EACH MONTH OF THE YEAR
After U S Department of Agriculture Yearbook 1955
WATER INFORMATION CENTER INC

Figure 4-9. Distribution of Runoff, by Region and by Season
(Source: Miller et al., 1962)

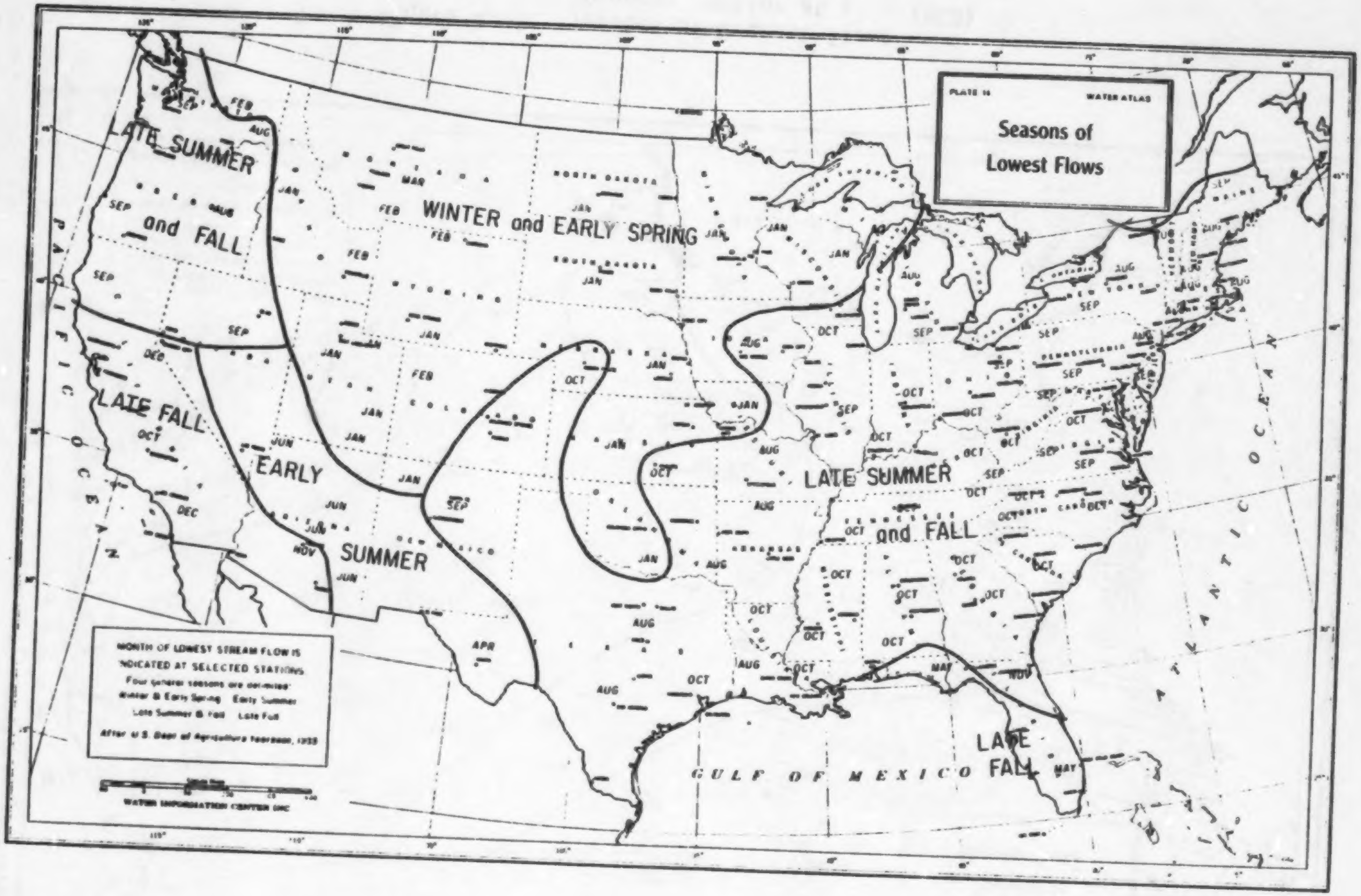
PLATE 14
WATER ATLAS
Seasons of Lowest Flows
LATE SUMMER and FALL
WINTER and EARLY SPRING
LATE FALL
EARLY SUMMER
LATE SUMMER and FALL
LATE FALL
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
MONTH OF LOWEST STREAM FLOW IS INDICATED AT SELECTED STATIONS
Four general seasons are delimited:
Winter & Early Spring   Early Summer
Late Summer & Fall   Late Fall
After U.S. Dept of Agriculture Yearbook, 1955
WATER INFORMATION CENTER INC

Figure 4-10. Seasons of Lowest Flows
(Source: Miller et al., 1962)

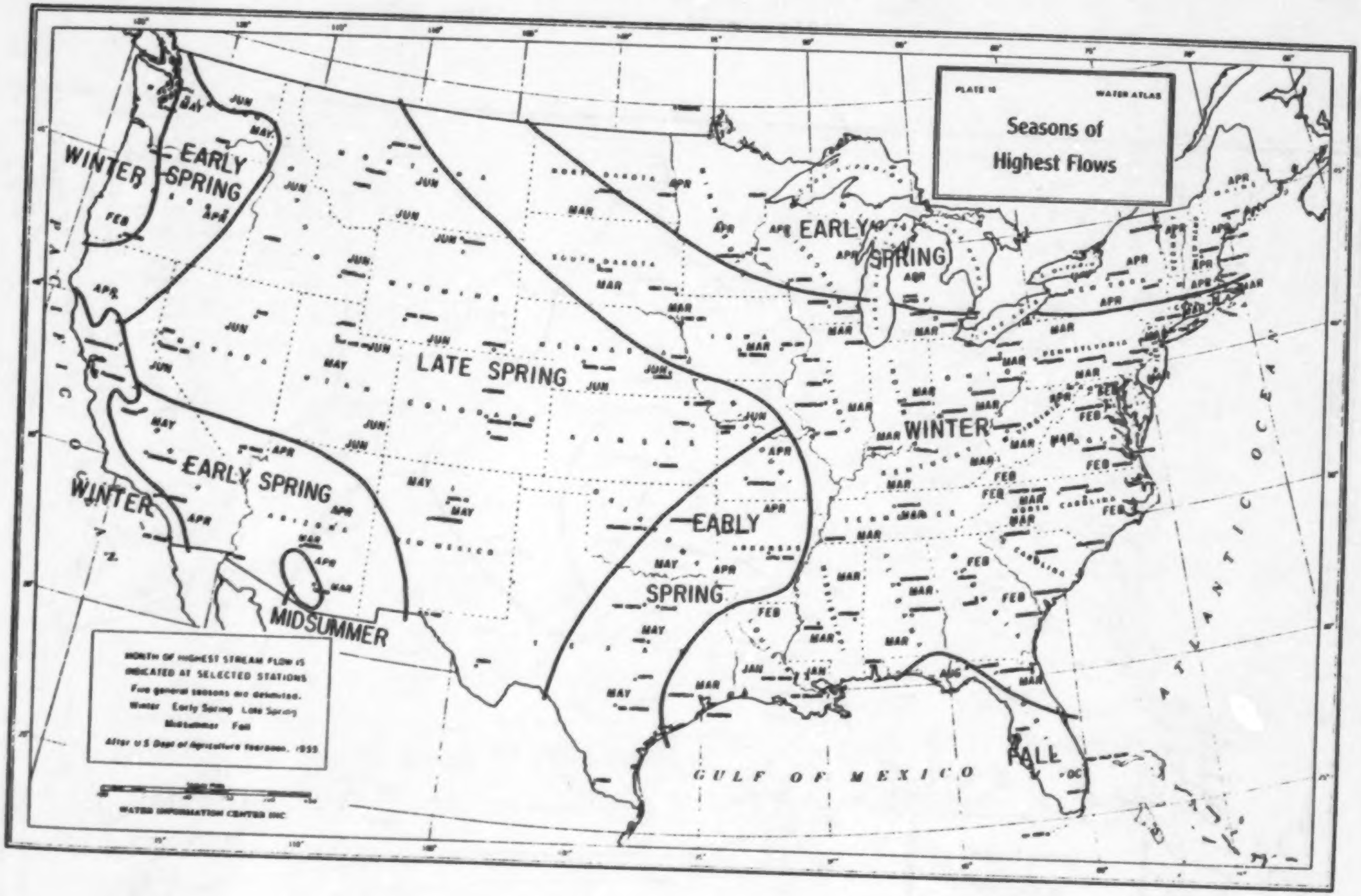
PLATE 15
WATER ATLAS
Seasons of Highest Flows
WINTER
EARLY SPRING
LATE SPRING
EARLY SPRING
WINTER
EARLY SPRING
WINTER
EARLY SPRING
EARLY SPRING
MIDSUMMER
FALL
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
MONTH OF HIGHEST STREAM FLOW IS INDICATED AT SELECTED STATIONS
Five general seasons are delimited.
Winter Early Spring Late Spring
Midsummer Fall
After U S Dept of Agriculture Yearbook, 1955
WATER INFORMATION CENTER INC

Figure 4-11. Seasons of Highest Flows
(Source: Miller et al., 1962)

Survey (USGS). Streamflow may be translated into a suspended sediment loading by various means (sediment rating curves, site-specific or regional empirical relationships; or by direct measurement at a few USGS stations), so for the remainder of this discussion we will use streamflow as a surrogate for suspended solids concentration.

The daily stream gage data used to develop Figure 4-9 may be reformatted to develop the flow-duration curve for a given gage. The flow-duration curve (Figure 4-12) shows the proportion of days during a period of record that a given level of flow is recorded, and may be used to show the cumulative time over which a given flow (or sediment level) is exceeded. While such a curve will suggest frequency of violation that might be expected once a criterion is set, it will not be particularly helpful in actually setting criteria because it depicts cumulative events of a given duration rather than the duration of individual events.

4.3.4 TIME-CONCENTRATION TOXICITY RELATIONSHIPS

The 'toxicity' of suspended solids to aquatic life is discussed in Chapter 3. The information in Chapter 3 was selected to illustrate the fact that the effect evoked by exposure to a given pollutant depends upon the length of exposure, and also upon the life stage of a particular organism. The duration of exposure is significant with toxic chemicals as well. Although there are substantial data bases available to document the toxicity of chemical pollutants, the data base descriptive of the effects of suspended solids on the biota is very sparse. The duration of exposure information of Chapter 3 points out a fallacy to basing criteria on a single number, such as a 96-hour LC50, and illustrates the need to consider the importance of duration of exposure, species, and life cycle stage as well.

A hypothetical study of a given suspended material and a given fish might generate a plot such as Figure 4-13. The figure shows that a given effect is seen after a 40-day exposure to 1.0 units of sediment, or to a 12-day exposure to 2.0 units. The specific design of experiments needed to generate such a curve is properly the domain of the toxicologist and is beyond the scope of this report. Regardless, it is important to note that a single value criterion, such as a 96-hour LC50 (which in Figure 4-13

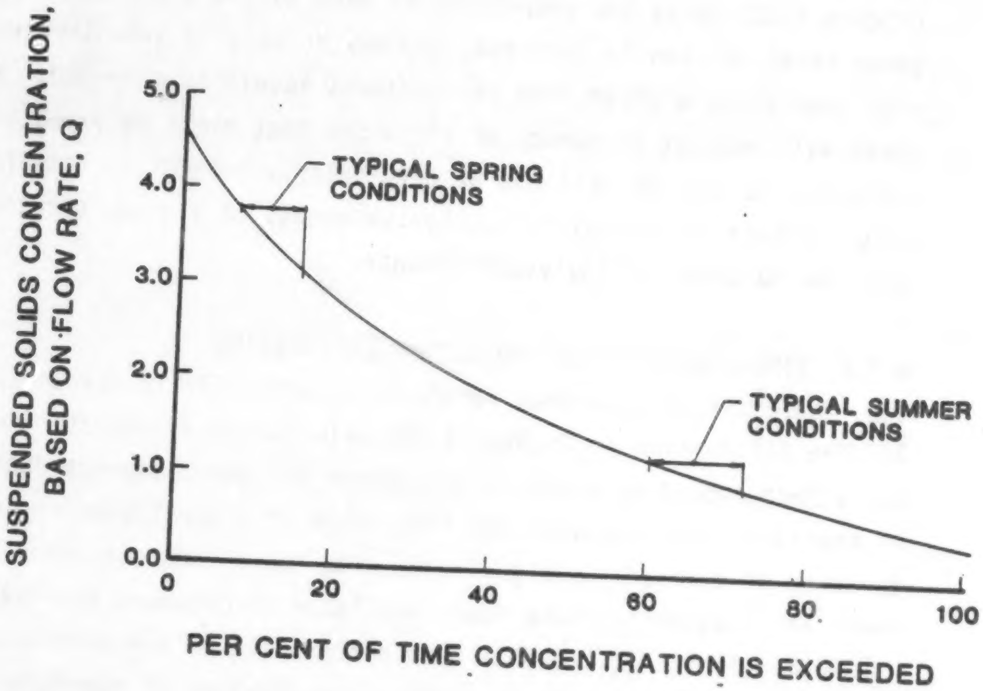

Figure 4-12. Typical Flow-Duration Curve

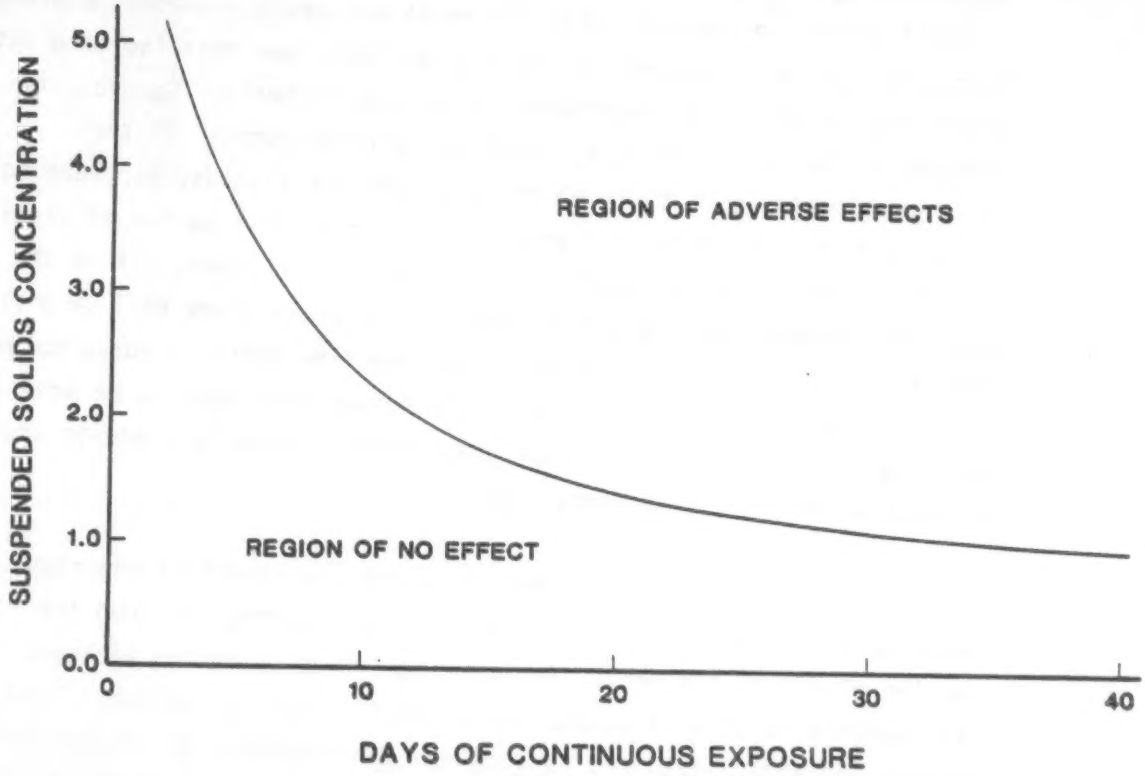

Figure 4-13. Hypothetical Concentration-Duration Plot of Adverse Effects Response for Exposure of a Fish to Suspended Solids.

corresponds to a concentration of 4.0 units), may not be sufficient because it does not adequately protect against longer periods of exposure, and may overprotect during short periods of exposure.

Figure 4-13 also suggests that a fish may be able to withstand a heavy exposure for a short period of time, without effect. The 'no effect' region is important in two ways: first, it suggests that a single extreme rainfall event, an outlier, with its resultant heavy suspended sediment load, may not be of consequence to a given fish, and that isolated extreme events may be of little importance in setting criteria. Second, it provides a tie to Figure 4-12, the flow duration curve. If the concentration-duration curve shows no effect for a 12-day exposure to 2 units, and the flow-duration curve suggests that this period of exposure will not occur, then one type of conclusion may be drawn. If on the other hand the concentration-duration relationship shows there will be a problem with a 1 unit exposure for 30 days, and the flow-duration curve shows that this combination is likely to occur, decisions will have to be made as to what level of protection to incorporate into a criterion, and/or what might be done to reduce the sediment load.

The question of what might be done to control sediment is important. Most sediment in a river is derived from nonpoint sources, or from the resuspension of bottom sediment. To the extent that suspended sediment is attributable to point sources, urban runoff, poor agricultural land management, or activities such as logging, construction, or placer mining, controls may be feasible. Otherwise, the sediment in a river is a background presence which may fluctuate with hydrologic events, but which is beyond easy means of control.

For those cases where there are natural and anthropogenic, point and nonpoint, sources of sediment, it may be fruitful to look beyond the flow-duration curve in order to distinguish natural from controllable sources. In the course of developing the flow-duration curve, resolution is lost and it is not possible to distinguish how long a particular concentration persists. One can only say that a given concentration occurred for a certain portion of the year.

One way to obtain better resolution is to take the daily flow (sediment concentration) record (Figure 4-14) and analyze this for various flow windows, or periods of time, over which a given concentration persists.

Using the hypothetical example of Figure 4-14 to illustrate, for a concentration of 2 we have one 90-day exceedance, and two 10-day exceedances. For a concentration of 3, we have one 20-day, one 10-day, and one 5-day exceedance. Continued evaluation would permit construction of the type of plot presented in Figure 4-15, from which one is able to tell how many times a given concentration and a given duration of sediment occurred in the water body.

Combining Figure 4-13 and Figure 4-15 (Figure 4-16) provides a means for the decisionmaker to relate toxicity data to hydrologic data. The upper portion of Figure 4-16 enables an assessment of risk attached to a given concentration or period of exposure. For example, the figure shows that fish can withstand a 12-day exposure to a concentration of 2 units, and a concentration of 2 units is likely to be equalled or exceeded about 10 times. Translation of number of exceedances to percent of total record provides an estimate of risk. For example, if this were a 20-year period of record, there is a likelihood of 0.5 events per year where the concentration of 2 units or greater will be violated over a 12-day period.

Figure 4-16 also shows, for a 12-day period of exposure, that a concentration of 1.0 will be exceeded 16 times, and a concentration of 3.0 will be exceeded 6 times. A concentration between 1.0 and 2.0 lasting 12 days will occur 4 times, but this is of no concern since a concentration less than 2.0 will evoke no adverse effects. In contrast, a concentration greater than 2.0 will evoke adverse effects, and a 12-day concentration between 2.0 and 3.0 may be expected to occur 6 times for the period of record. The significance of this incursion into the region of adverse effects depends upon such factors as the severity of the adverse effect, the time of year when these incursions are likely to occur, and the most sensitive stage of the life cycle that will be found for a given species when these incursions occur.

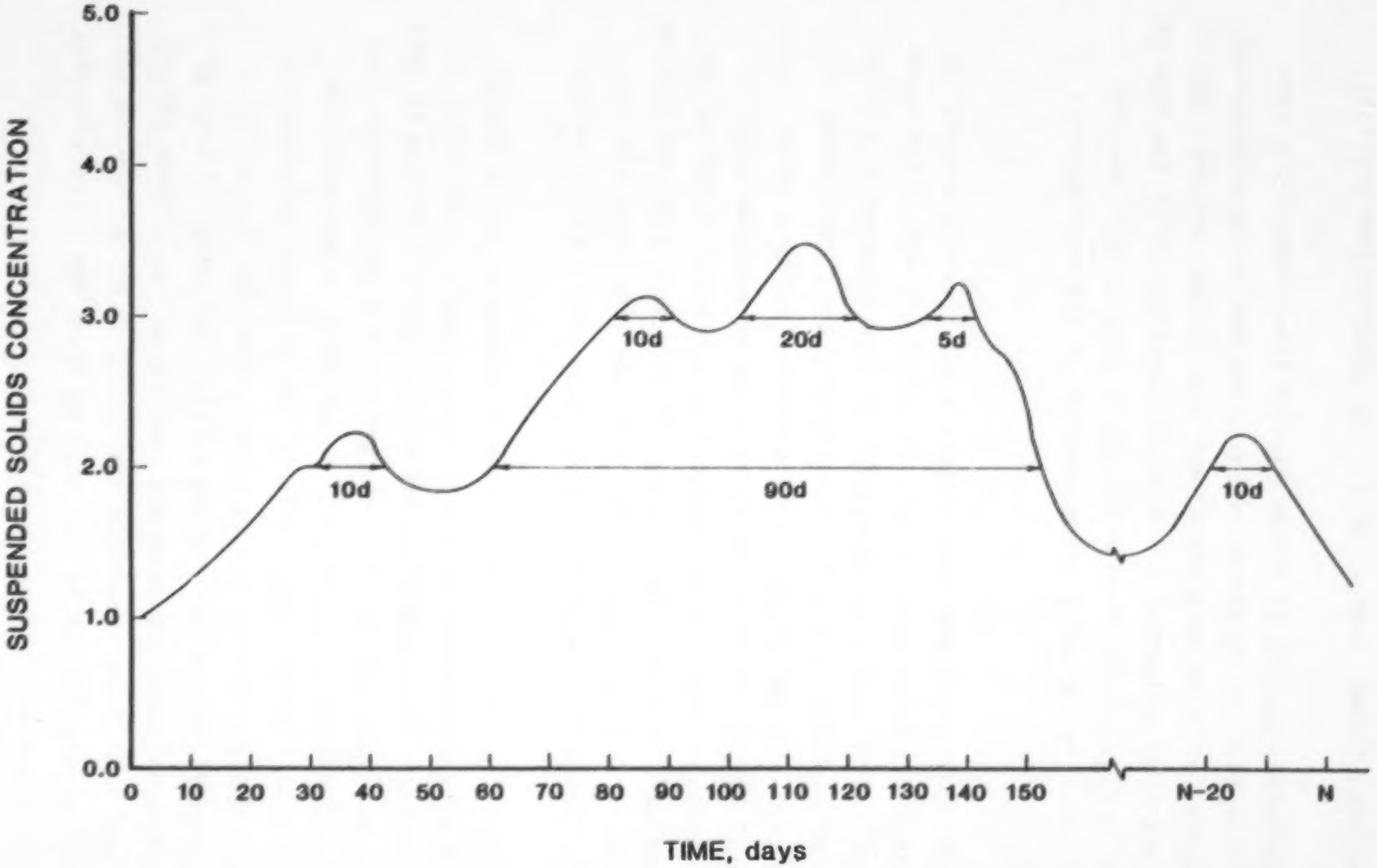

Figure 4-14. Hypothetical Daily Record for Suspended Solids

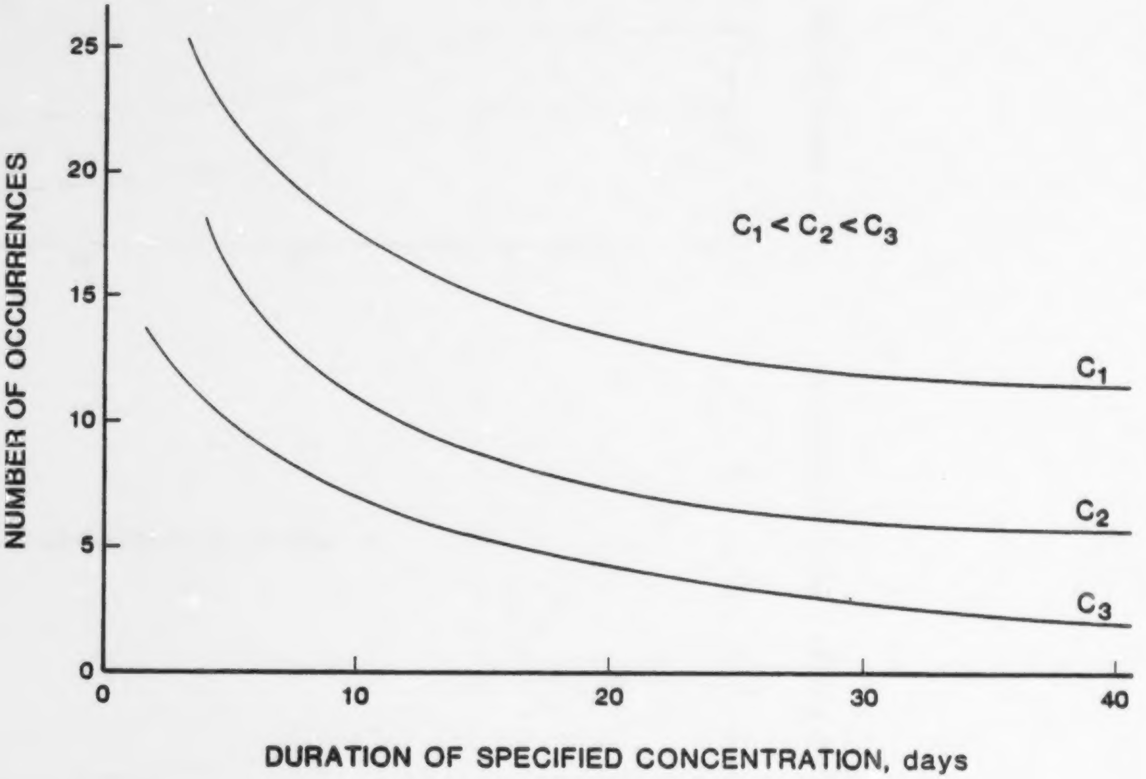

Figure 4-15. Number of Times a Given Concentration is Exceeded for a Given Number of Days

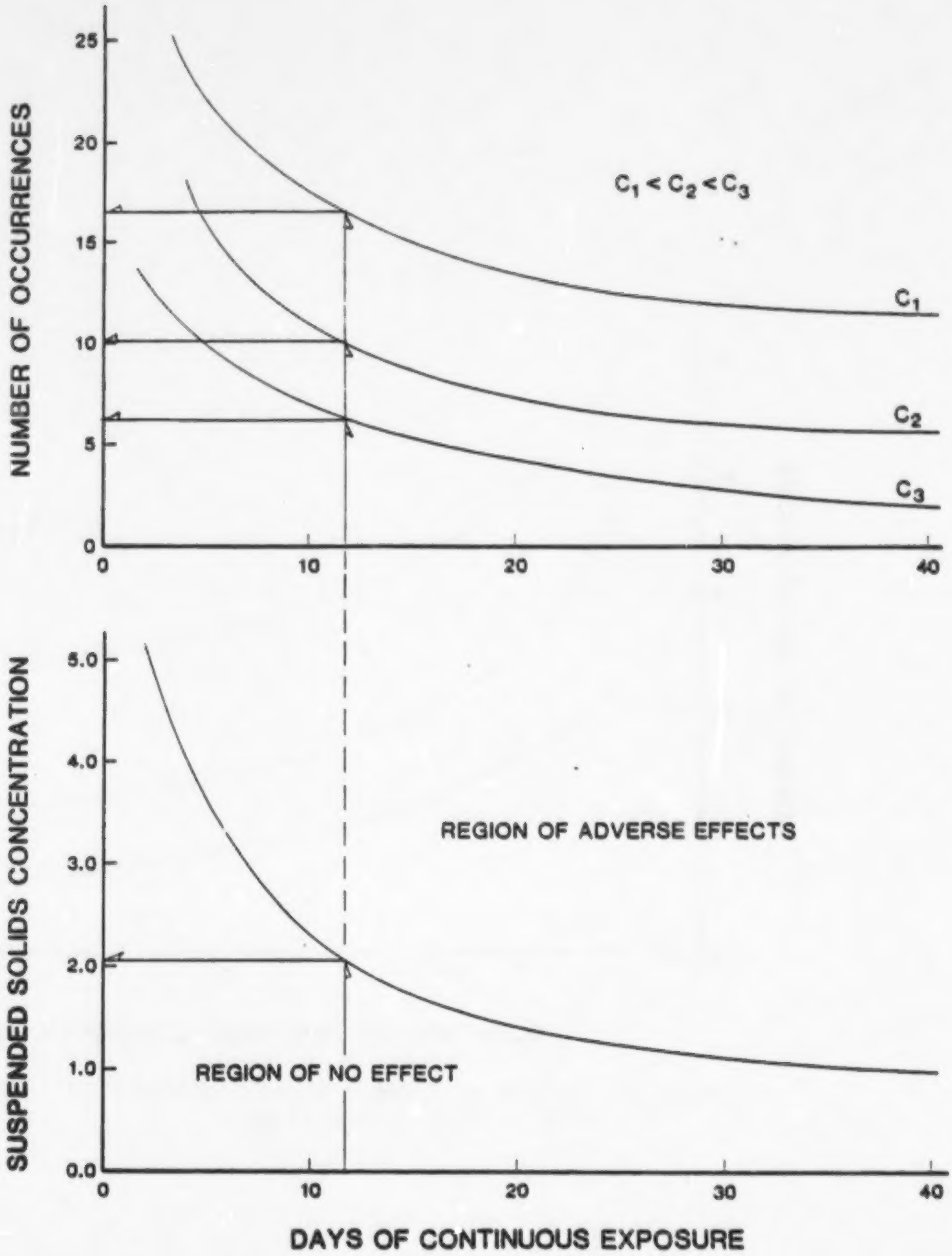

Figure 4-16. Relationship of Suspended Solids Adverse Effect Level to Likelihood of Occurrence of a Given Suspended Solids Concentration

A water quality criterion for suspended sediment cannot be specified without first defining what adverse effects are to be guarded against, and for what types of organisms and life stages (so as to develop the equivalent of Figure 4-13); and without first quantifying what the natural and/or background levels of sediment will be on a seasonal and a site-specific basis (since it would make no sense to specify a criterion that would automatically be violated by background conditions). It may be difficult to distinguish controllable anthropogenic loadings from background sources, particularly so when the anthropogenic loading is small compared to the background loading.

Since background concentrations will vary with hydrologic events, and since the susceptibility to sediment varies with stage of the life cycle, it will be necessary to specify seasonal criteria. Criteria will be most important during average and during low flow periods when background levels are low compared to anthropogenic contributions. High flow periods, many of which might be considered to be outliers, extreme storm events, do not really fall within the realm of criteria since the major natural sources of sediment (erosion and channel scour) during these periods cannot be controlled, and controls on anthropogenic sources may not be adequate.

There are many statistical tests that might be used to identify outliers. One possible test is found in the lognormal distribution. The flow in a river tends to follow a lognormal probability distribution. Since sediment levels are directly related to flow, we can also assume that sediment levels are lognormally distributed. Specifying a probability level for flows that are abnormally high provides a means for identifying flows in the historical record that represent extreme events during which sediment levels cannot be controlled.

4.4 ADDITIONAL FACTORS THAT MUST BE CONSIDERED

The preceding section outlined how a statistical analysis of hydrology (and sediment loadings, by association) could be combined with toxicity data as an approach to specifying criteria for suspended solids. This discussion is elementary, and does not address a number of problems and questions that must be considered in the development of criteria. Some of these questions are introduced below.

1. Adequacy of data base. A great deal of material is available in the literature which is descriptive of the effects of suspended and settled sediment on the biota of a stream. However, very little of this includes enough detail to permit establishment of criteria. If a procedure were to be used that is analogous to the development of criteria for toxic chemicals, a much more substantial database on sediment effects would be required.

2. Definition of adverse effects. There are many adverse effects to the biota of a stream that can be attributed to suspended sediment. These may range from inconvenience to sight feeding fish, to lethality because of clogging of the gills. The fact that fish persist in natural streams that carry an occasionally heavy sediment load suggests that lethality may not be a problem. Where possible, fish may simply go elsewhere, and return when sediment concentrations return to manageable levels. This also raises the question of the need to distinguish between suspended sediment, and settled sediment. How do we address the fact that suspended sediment may not be a problem for a given fish, but may become a problem when velocities decline and solids settle out to smother breeding grounds, or eggs, or macroinvertebrates? How do we address the fact that many fish and macroinvertebrates thrive when the bottom is covered by fine sediments?

3. Definition of sediment. The quality of a suspended sediment is determined by such factors as particle size, mineral content, and organic content. Particle size may vary with water velocity, and will vary with physiographic region. To the extent that sediment may have a direct physical effect on the biota, a consideration of particle size is important. Particle size can be handled statistically, and could be related to flow, and to duration of exposure to various concentrations of suspended sediment. Toxic chemicals may be sorbed to sediment particles, and may be tied up and

rendered toxicologically inert. The extent to which toxics are inactivated may depend upon the organic or the mineral content of the sediment, and will differ from toxic chemical to toxic chemical. The question should be considered as to whether sediment quality is important to the establishment of criteria, or whether all sediments can be treated alike.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The previous chapters address the causes and impacts of suspended solids on water quality. The following conclusions may be drawn:

- Suspended solids concentrations vary spatially and temporally due to the complex cause and effect relationship between geology, topography, climate, land cover, and runoff.
- The habitat preferences and life cycles of aquatic life may be correlated with geology, topography, climate, and runoff.
- Suspended sediment affects different species of aquatic life differently.
- The complexities of sedimentation illustrate that a single national criteria may not be appropriate.
- Regional correlations exist between the processes resulting in sedimentation and species behavior that can be used as a basis for criteria.
- Regional/seasonal relationships appear to be the most feasible approach for setting natural condition hydrologic criteria.

5.2 METHODOLOGY RECOMMENDATION

The following elements are recommended in establishing suspended solids criteria:

1. Identification of regions. SCS land resource units (Soil Conservation Service, 1963) are recommended as the basis for spatial regionalization. SCS land resource units are based on climate, soils, topography, natural vegetation, water resources, and land use--all factors involved in sedimentation.
2. Identification of seasons. Hydrologic seasons within each region are recommended based on annual precipitation distributions.
3. Development of flow/sediment rating curves for rivers, lakes, and estuaries. Statistical analyses must be performed on gaged sites to develop flow-duration frequency curves. Rating curves relating flow, sediment, and drainage area within seasons within regions in natural drainage basins can be developed. Duration and frequency for criteria will be based on species tolerance analysis. Long term levels will reflect long term seasonal averages omitting single event short duration large sediment loads. Short term levels will consider single event conditions.

4. Identification of short and long term tolerances of species or families to suspended solids. Definition of short and long term must be defined.

.3 FUTURE WORK

ach of the four elements listed above under Methodology will require ndividual attention. Elements 1, 2, and 3 are based on a detailed nalysis of the historical record of stream flow and sediment loading atterns, soil types, and general physiography. From this, definitions can e developed of regions, and of seasons within these regions, and specific ediment load and duration relationships can be characterized.

lement number 4 may be approached in stages. In the first stage a oncerted effort should be made to search the literature for data that ould augment the time-concentration information presented in Chapter 3. his would enable a first pass at the development of time-concentration urves such as Figure 14-3, that could then be correlated with hydrologic ata, as an approach to sediment criteria (Figure 4-16). While this is eing done, attention must also be given to development of a methodology by hich time-concentration curves for a number of species or families or ndividual fish, could be combined to produce a curve that is representaive of all aquatic life.

he development of time-concentration relationships based on existing nformation is an important first step, however, it is not likely that ufficient data will be found to address element 4 adequately, and it will e necessary to design and conduct bioassay tests that will enable a clear nderstanding of the several factors--type of sediment, types of test rganism, water quality parameters, intensity and duration of exposure, tc.--that are important to the development of sediment criteria.

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APPENDIX A

TOLERANCES OF FISH TO SUSPENDED SOLIDS (TURBIDITY) AND SEDIMENT

SOURCE: Muncy, et al., 1979

TABLE A-1

Warmwater Fishes which are Intolerant of Suspended Solids (Turbidity) and Sediment. Numbers refer to references listed in Table A-4.

Species	Effect		Impact through	
	Spawning	General	Suspended solids	Sediment
Ichthyomyzon castaneus	7			7
Acipenser fulvescens	7	27,29		7,27,29
Polyodon spathula	21	29		21,29
Lepisosteus platostomus		27		27
Amia calva	25,30		25, 30	
Hiodon tergisus		27,29	27, 29	
Esox lucius	24,28,30		30	24,28,30
Esox masquinongy		27,30	27, 30	
Clinostomus elongatus		8,30		8,30
Dionda nubila		29		29
Exoglossum laurae		27,30		27,30
Exoglossum maxillingua		25		25
Hybopsis amblops		29,30	29	29,30
Hybopsis dissimilis		27,30		27,30
Hybopsis x-punctata		8,27,30		8,27,30
Nocomis biguttatus	7			7
Nocomis micropogon		27,30	27, 30	27,30
Notropis amnis		5	5	
Notropis boops		29,30	29, 30	29,30
Notropis cornutus		7		7
Notropis emiliae		27,29,30	27, 29, 30	27,29,30
Notropis heterodon		8,13,30	8, 13, 30	8,13,30
Notropis heterolepis		7,30	7, 30	
Notropis hudsonius		8,30	30	8
Notropis rubellus		2,30	2, 30	30
Notropis stramineus		7,8,30	7, 30	7,8
Notropis texanus		29		29
Notropis topeka		8		8

TABLE A-1

Warmwater Fishes which are Intolerant of Suspended Solids (Turbidity) and Sediment. Numbers refer to references listed in Table A-4.

Species	Effect		Impact through	
	Spawning	General	Suspended solids	Sediment
Notropis volucellus		30	30	
Carpiodes velifer		29	29	
Cycleptus elongatus		7,29		7,29
Erimyzon oblongus		30	30	
Erimyzon sucetta		27,30	27, 30	27,30
Hypentelium nigricans		7,8,25,30	25, 30	7,25,30
Lagochila lacera		30	30	30
Minytrema melanops		7,30	7, 30	
Moxostoma carinatum		30	30	30
Moxostoma duquesnei		8,25,30	8, 30	8,25
Moxostoma valenciennesi		8,27,30	8, 27, 30	27,30
Ictalurus furcatus		5,7,30	5, 30	7,30
Noturus flavus		8		8
Noturus furiosus		30	30	
Noturus gyrinus		25,30	30	25,30
Noturus miurus		7,25	7, 25	
Noturus trautmani		27	27	27
Pylodictis olivaris		30	30	30
Percopsis omiscomaycus		30		30
Fundulus notatus		30	30	
Labidesthes sicculus		30	30	
Culaea inconstans		30	30	
Ambloplites rupestris		29	29	
Lepomis gibbosus		9,25,30	9, 25, 30	9
Lepomis megalotis		29,30	29, 30	
Micropterus dolomieui	23,30	23,30	23, 30	23,30
Micropterus salmoides		23,30	23, 30	23,30
Ammocrypta asprella		29,30		29,30
Ammocrypta clara		29		29
Ammocrypta pellucida		27,30		27,30

TABLE A-1

Warmwater Fishes which are Intolerant of Suspended Solids (Turbidity) and Sediment. Numbers refer to references listed in Table A-4.

Species	Effect		Impact through	
	Spawning	General	Suspended solids	Sediment
Etheostoma blennioides		30		30
Etheostoma exile		27, 30	27,30	
Etheostoma tippecanoe		27		27
Etheostoma zonale		29		29
Perca flavescens	25,30	25,30	25,30	25,30
Percina caprodes		7,30	7	30
Percina copelandi		27,30	27, 30	27,30
Percina evides		29,30	30	29
Percina maculata		30	30	
Percina phoxocephala		27,30	27, 30	27,30

TABLE A-2

Warmwater Fishes which are Tolerant of Suspended Solids and Sediment. Numbers refer to references listed in Table A-4.

Species	General tolerance	Preference for turbid systems
Scaphirhynchus albus	7	
Dorosoma cepedianum		30
Hiodon alosoides	25, 30	
Carassius auratus	30	
Couesius plumbeus	3	
Cyprinus carpio		19, 25, 30
Ericymba buccata	5, 14, 30	27
Hybopsis gelida	5	
Hybopsis gracilis	5	
Notropis dorsalis		27
Notropis lutrensis		7, 27
Orthodon microlepidotus	19	
Phenacobius mirabilis	7, 30	
Phoxinus oreas	9	
Pimephales promelas	7, 30	29
Pimephales vigilax	7, 30	
Plagopterus argentissimus	5	
Semotilus atromaculatus	7, 22	29
Catostomus commersoni	9, 30	
Ictiobus cyprinellus	7, 25, 30	
Moxostoma erythrurum	30	
Ictalurus catus	30	
Ictalurus melas	7	25, 30
Aphredoderus sayanus	30	
Lepomis cyanellus	7, 30	
Lepomis humilis	7, 27, 30	
Lepomis microlophus	29	
Micropterus punctulatus	11, 23, 30	
Micropterus treculi	18, 23	
Pomoxis annularis	12, 26, 30, 31	
Pomoxis nigromaculatus	7, 12, 20, 25	
Etheostoma gracile	7	
Etheostoma microperca	30	
Etheostoma nigrum	30	
Etheostoma spectabile	7, 30	
Stizostedion canadense	6, 25, 30	
Aplodinotus grunniens	30	

TABLE A-3

Warmwater Fishes for which Contradictory Information was found on their Tolerance or Intolerance to Suspended Solids and Sediment. Numbers refer to references listed in Table A-4.

Species	**Tolerant**	**Intolerant**
Campostoma anomalum	7	30
Clinostomus funduloides	9	27
Hybognathus nuchalis	2, 7	30
Notropis buchanani	7	30
Notropis spilopterus	30	7, 10
Notropis umbratilis	5, 29	7, 30
Pimephales notatus	30	7
Rhinichthys atratulus	9	30
Carpiodes carpio	7, 30	5
Ictalurus nebulosus	20	30
Ictalurus punctatus	7, 16, 17	4, 25, 30
Morone chrysops	20	25, 30
Lepomis gulosus	15	30
Lepomis macrochirus	20	9, 30
Etheostoma flabellare	25, 30	9
Stizostedion vitreum	1, 20, 25	27, 30

TABLE A-4

References used in Tables A-1, A-2 and A-3

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APPENDIX B

SOIL CONSERVATION SERVICE
LAND RESOURCE REGION DESCRIPTIONS

LAND RESOURCE REGIONS

The United States (48 conterminous States) has been divided into 156 major land resource areas. These areas have been delineated on the basis of similarities in relationships to agriculture; the emphasis is on combinations or intensities of problems in soil and water conservation, or both. They are characterized by particular combinations or patterns of soils (including slope and erosion), climate, water resources, land use, and kinds of farming. They are designated on the land resource region map by numbers and names. They are not described in this Atlas, but their descriptions will be available in a later Soil Conservation Service publication.

The 156 major land resource areas have been grouped into 20 land resource regions, designated on the map by large capital letters and names. In this grouping, the objective has been to retain as much similarity as possible in agricultural relationships within each region. Brief descriptions of these regions follow. In the interest of brevity, the information about soils is given in terms of great soil groups, a high category in the current soil classification system. Brief general descriptions of the great soil groups in alphabetical order follow the descriptions of the 20 land resource regions.

A NORTHWESTERN FOREST, FORAGE, AND SPECIALTY CROP REGION

This is a region of steep mountains and narrow to broad, gently sloping valleys and plains. The annual precipitation ranges from 40 to 70 inches over much of the region, but it is 30 inches or less in some valleys and as much as 200 inches in some of the higher mountains. All parts of the region have a pronounced dry season in summer. The average annual temperature is 50° F. over most of the region, but it is 40° F. or less in some of the mountains. The freeze-free season is more than 200 days in the valleys, but the length decreases markedly with elevation in the mountains.

Reddish-Brown Lateritic soils, Yellowish-Brown Lateritic soils, Brown Forest soils, Ando soils, Sols Bruns Acides, and Lithosols are the principal soil groups in the mountains and uplands. Alluvial soils, Brunizems, Brown Podzolic soils, and Humic Gley soils are extensive in the valleys.

The mountains are heavily forested, and lumbering is a major industry in the region. Dairy farming is important in the valleys with higher rainfall; grain crops, grass and legume seeds, fruits, and horticultural specialties are grown extensively in the drier valleys.

B NORTHWESTERN WHEAT AND RANGE REGION

This region consists mainly of smooth to deeply dissected plains and plateaus, but it includes some mountain ranges. The annual precipitation ranges from about 10 to 20 inches; there is very little rainfall in summer. The average annual temperature is 45° F.; the freeze-free season ranges from 120 to 160 days except in the mountains where it is shorter.

Brown soils, Chestnut soils, Sierozems, Chernozems, and Brunizems, all derived mainly from loess, are dominate over much of the region. Ando soils are conspicuous in places where the parent materials consist mostly of volcanic ash. Lithosols occur on the steep slopes underlain by basalt and lava. Alluvial soils on the flood plains are important for agriculture.

Wheat grown by dryfarming methods is the major crop over most of the region, but oats and peas are important also. Fruit, mainly apples, is a major crop in the western part. Grazing is the major land use in the drier parts, especially in the west.

C CALIFORNIA SUBTROPICAL FRUIT, TRUCK AND SPECIALTY CROP REGION

This is a region of low mountains and broad valleys. It has a long, warm growing season and low precipitation. The annual rainfall ranges from 30 inches to less than 10 inches; very little occurs from late April through October. The average annual temperature is 60° F. over most of the region, but it is as low as 45° F. at some of the higher elevations. The freeze-free season averages 250 days for much of the region, but it ranges from 150 days or less in some of the higher mountains to more than 300 days in the valleys in the south.

Noncalcic Brown soils, Grumusols, and Brunizems are extensive on the uplands and older terraces throughout the region, but Alluvial soils and Humic Gley soils on flood plains and alluvial fans are the most important soil groups for agriculture. Many of the soils on flood plains and low terraces are affected to varying degrees by salts, so that skillful management is required for satisfactory crop yields.

This region has a wide variety of crops and agricultural enterprises. Citrus fruits, other subtropical and tropical fruits, and nuts are major crops in the southern half. Many kinds of vegetable crops, grown mainly under irrigation, are produced throughout the region. Rice, sugar beets, cotton, grain crops, and hay are also important. Dairying is a major enterprise near the large cities. Beef-cattle production on feed lots and range is also important.

D WESTERN RANGE AND IRRIGATED REGION

This is a semidesert to desert region of plateaus, plains, basins, and many isolated mountain ranges. The annual precipitation is 10 inches or less over most of the plains and basins, but it is slightly more on the higher mountains. In the southeastern part the maximum amount of rainfall occurs during the warm season, but elsewhere precipitation is higher in the cool season. The average annual temperature for the region as a whole is 50° F., but it ranges from 42° F. at the higher elevations in the north to more than 70° F. in some of the lowlands in the south. The freeze-free season ranges from less than 120 days in the north and in some of the higher mountains to more than 200 days in the south.

Sierozems, Desert soils, Brown soils, and Grumusols are extensive on the plains, plateaus, and valleys throughout the region. Chestnut soils, Chernozems, and Gray Wooded soils are on some of the mountain slopes. Alluvial soils, Solonetz soils, and Solonchak soils in the plains and basins and Lithosols on the mountain slopes are also important.

Much of the land in this region is used for range, but irrigation agriculture is practiced where water is available and soils are favorable. Feed crops for livestock occupy much of the irrigated land, but peas, beans, and sugar beets are grown in many places. Cotton and citrus fruit are important in southwestern Arizona.

E ROCKY MOUNTAIN RANGE AND FOREST REGION

Rugged mountains dominate this region, but some broad valleys and high plateau remnants are included. The annual precipitation ranges from 20 to 40 inches over much of the region, but it is less than 10 inches in some valleys and 50 inches or more on some of the mountain peaks. The average annual temperature is 40° to 45°F. The freeze-free season is 100 to 120 days in the valleys and basins, but the length decreases to 60 days or less with increasing elevation in the mountains. Some of the highest mountains are covered by glaciers and have perpetually frozen ground.

Chestnut soils, Chernozems, and Brown soils are the dominant soil groups in the valleys and on the lower mountain slopes. Gray-Brown Podzolic soils, Gray Wooded soils, Podzols, and Alpine Meadow soils are on the upper mountain slopes and crests. Lithosols are extensive on the steep mountain slopes, and Alluvial soils are important in the valleys.

Grazing is the leading land use in both the valleys and the mountains, but lumbering is important in some of the forested mountain areas. Recreational land uses are important throughout the region. Irrigation agriculture is practiced in some of the valleys and dryfarming in others. Grain and forage for livestock are the main crops; beans, sugar beets, peas, and seed crops are also grown where soils, climate, and markets are favorable.

F NORTHERN GREAT PLAINS SPRING WHEAT REGION

The fertile soils and the dominantly smooth topography are favorable for agriculture in this region, but the low rainfall and the short growing season impose severe restrictions on the crops that can be grown. The annual precipitation ranges from 11 to 24 inches; a large part of it occurs during the growing season. The average annual temperature is 40°F. The freeze-free season ranges from 110 to 125 days, increasing in length from north to south.
Chernozems and Chestnut soils are dominant over most of the region, but Brown soils cover the western part. Lithosols on steep slopes, Solonetz soils, Solonachak soils, and Humic Gley soils on terraces and in depressions, and narrow bands of Alluvial soils along the major streams are also important.

The production of spring wheat by dryfarming methods dominates the agriculture of the region. Other spring grains, flax, and hay are also produced. Potatoes are grown in many places, and sugar beets and corn are important in the Red River Valley in the east.

G WESTERN GREAT PLAINS RANGE AND IRRIGATED REG.

This is the section of the Great Plains where unfavorable soils, strong slopes, or low moisture supplies make success at dryfarming very uncertain. The annual precipitation ranges from 11 to 20 inches, but it is highly variable from year to year. The average annual temperature is 45°F. for the region as a whole, but it ranges from 40°F. in the north to 60° F. in the south. The freeze-free season ranges from 105 days in the north to 180 days in the south.

Chestnut soils are dominant over much of the region, but Brown soils are important in the west. Lithosols on the more sloping parts of the dissected areas, Regosols on sands, and Alluvial soils in bands on flood plains are also extensive. Less extensive, but important locally, are Grumusols on heavy clay and Solonetz soils in depressions and on terraces.

A large part of the region is in range, but some wheat is produced by dryfrarming methods, mainly along the eastern margin. Irrigation agriculture is practiced along some of the major rivers. Forage and grain for livestock are the principal crops on irrigated land; potatoes, sugar beets, and vegetable crops are important locally.

H CENTRAL GREAT PLAINS WINTER WHEAT AND RANGE REGION

Soils, topography, and climate are more favorable for agriculture in this region than in the Great Plains to the west. The longer freeze-free season permits a greater variety of crops to be grown than in the northern Great Plains. The average annual precipitation is 25 inches, but it ranges from 18 to 32 inches, increasing from northwest to southeast. More rain falls in summer than in the rest of the year. The average annual temperature is 50° to 55° F. The average freeze-free season is 180 days, but the length ranges from 160 to 215 days, increasing from north to south.

The important soils in the northern part are in the Chernozem and Chestnut groups. Reddish Prairie soils and Reddish Chestnut soils are extensive in the south. Lithosols on steep slopes, Regosols on deep sands, and Alluvial soils on flood plains are common throughout the region.
Cash-grain farming with wheat as the principal crop is the major agricultural enterprise on most of the better soils. Grain sorghum is grown in many of the drier areas. In the southern part of the region where the freeze-free period exceeds 200 days, cotton is grown extensively under irrigation from wells. The steeply sloping shallow and sandy soils are used for range.

I SOUTHWESTERN PLATEAUS AND PLAINS, RANGE AND COTTON REGION

This region consists of the warmer part of the southern Great Plains. The moderate precipitation is accompanied by high temperatures, so that the precipitation effectiveness is low. The average annual precipitation is 25 inches; usually much of it occurs in spring and autumn. The average annual temperature is 67°F., and the freeze-free season averages 250 days.

The soils on the deeper coarse- and medium-textured materials are mostly members of the Reddish Chestnut and Reddish Prairie groups. Grumusols on limestones and marls and Lithosols and Calcisols on hilly to steep slopes on all kinds of parent material are also fairly extensive.

Range is the dominant land use over most of the region, but some wheat, other small grains, and grain sorghum are grown where soils, topography, and moisture supplies are favorable. In the southeastern part, cotton grown under irrigation is important. Citrus fruits and winter vegetables are grown along the lower Rio Grande Valley.

J SOUTHWESTERN PRAIRIES, COTTON AND FORAGE REGION

This region consists of the prairies and the timbered areas of eastern Texas. The average annual precipitation ranges from 30 to 38 inches. The average annual temperature is 65°F., and the freeze-free season ranges from 220 to 260 days.

Grumusols, Rendzinas, and Lithosols on limestone and chalks are the more extensive soils in the region. Red-Yellow Podzolic soils, Planosols, and Reddish Prairie soils are also important groups.

The region is intensively farmed. Cotton, grain sorghums, other feed grains, and hay are important crops. Most of the more sloping areas in the western part of the region are in open timberland, which is used for grazing.

K NORTHERN LAKE STATES FOREST AND FORAGE REG.

Poor soils and a cool, short growing season impose severe restrictions on agriculture in this region. The annual precipitation ranges from 22 to 32 inches; the heaviest rainfall occurs during the growing season. The average annual temperature is 40°F., and the freeze-free season ranges from 110 to 140 days.

Podzols on sandy parent materials and Gray Wooded soils on the finer textured parent materials are the dominant soils in the better drained areas. Bog soils, Humic Gley soils, Low-Humic Gley soils, and Ground-Water Podzols occupy the wetter uplands and depressions. Lithosols and rough stony land are extensive on hills and low mountains.

A large part of this region is forested, and lumbering and recreation are the principal uses. Mining is a major industry in all but the eastern part of the region. Forage and some grains for livestock are the main crops on the farmed areas. Potatoes are important locally.

L LAKE STATES FRUIT, TRUCK, AND DAIRY REGION

This region consists of nearly level to gently sloping, glaciated plains. The soils and climate are favorable for agriculture. The average annual precipitation is 33 inches and is distributed fairly evenly throughout the year. The average annual temperature ranges from 45° to 50°F. The freeze-free season is about 150 days, except in narrow belts adjacent to the Great Lakes where it is as much as 180 days.

Gray-Brown Podzolic soils are dominant throughout this region, but Humic Gley soils, Low-Humic Gley soils, and Bog soils are fairly extensive in the level areas and depressions.

The region has a wide variety of agricultural enterprises. Dairy farming is important, especially near the larger urban centers. Canning crops, corn, soft winter wheat, beans, and sugar beets are among the leading crops. Fruit growing is very important in a narrow belt adjacent to the Great Lakes. Rural residences occupy much land near many of the larger cities, and some farming is done on a part-time basis by people who earn their main living in the cities.

M CENTRAL FEED GRAINS AND LIVESTOCK REGION

Fertile soils and favorable climate make this one of the outstanding grain-producing regions of the world. The annual precipitation ranges from 26 to 42 inches; somewhat more than half falls during the growing season. The average annual temperature is 45° to 50°F. The freeze-free season averages 170 days; it ranges from 150 days in the north to 200 days in the southernmost parts.

Gray-Brown Podzolic soils in the east and Brunizems in the west are the dominant soils of the region. Humic Gley soils and Bog soils in the wet lowlands and Alluvial soils in bands along the major streams are also important.

Corn, soybeans, oats, and other feed grains are the most extensive crops of this region. Hay, winter wheat, and a variety of other crops are also grown. Much of the grain is fed to beef cattle and hogs on the farms where it is grown, but large amounts are shipped to other regions for use as livestock feed. Part is processed for food products and for industrial uses.

N EAST AND CENTRAL GENERAL FARMING AND FOREST REGION

This region is the borderland between the North and the South. It occupies the Appalachian mountains, valleys, and dissected plateaus and the Ozarks. The annual precipitation ranges from 42 to 54 inches, and the seasonal distribution is fairly even. The freeze-free season averages 180 days, but it ranges from 150 days to 200 days.

Sols Bruns Acides are the more extensive soils on the sandstones and acid shales of the mountain slopes and dissected plateaus. Red-Yellow Podzolic soils are on the limestones and the more deeply weathered shales. Reddish-Brown Lateritic soils are conspicuous in some limestone valleys and basins, but their total area is small. Alluvial soils along the many streams are of small total extent, but they are intensively used for cropland throughout the region.

Small general farms are characteristic of much of the region, but there are large dairy and livestock farms on some areas of the more favorable soils. Corn, small grains, and hay are the most extensive crops. Tobacco is an important cash crop, especially in the eastern two-thirds of the region. The steeply sloping areas, amounting to nearly one-half of the region, are mainly in forests, which are used both for recreation and timber production. A large part of the Nation's coal is mined in this region.

O MISSISSIPPI DELTA COTTON AND FEED GRAINS REGION

This region includes the flood plains and terraces of the Mississippi River south of its confluence with the Ohio River. The average annual precipitation is 50 to 55 inches. The average annual temperature is 65°F., and the freeze-free season is 220 to 240 days long. Low-Humic Gley soils, Humic Gley soils, Alluvial soils, and Grumusols are the extensive soil groups on the flood plains and low terraces. Red-Yellow Podzolic soils are important on the higher, silt-mantled terraces.

The soils throughout much of the region are naturally poorly drained and poorly suited to crops, but they are well suited to crops and are highly productive if artificially drained. Cotton, soybeans, corn, and hay are grown throughout the region. Rice in Arkansas and Louisiana and sugarcane in Louisiana are important crops locally. The wettest areas that are not artificially drained remain in forest and are important for hardwood-timber production.

P SOUTH ATLANTIC AND GULF SLOPE CASH CROP, FOREST, AND LIVESTOCK REGION

This is the traditional cotton region and consists of gently sloping to rolling Southern Piedmont and upper Coastal Plain. The average annual precipitation ranges from 45 to 55 inches; rainfall is considerably higher in midsummer than in the rest of the year. The average annual temperature is more than 60°F. The freeze-free season averages 240 days for the region as a whole, but it ranges from 220 to 290 days.

Red-Yellow Podzolic soils are dominant throughout the region. Reddish-Brown Lateritic soils on basic rocks are conspicuous locally as are Grumusols on some marls or soft limestones. Alluvial soils on the flood plains of the major streams are among the better crop-suited soils.

Cotton is the main cash crop throughout the region, but the acreage in cotton has been declining for many years. Peanuts and tobacco are also important, especially in the northeastern part of the region. The acreage in improved pasture has been increasing, and much of the more sloping land is being returned to forest.

R NORTHEASTERN FORAGE AND FOREST REGION

This region consists of relatively cool, humid plateaus, plains, and mountains. The annual precipitation ranges from 35 to 45 inches; more than one-half falls during the freeze-free season in most of the region. The average annual temperature is 40° to 45° F. The freeze-free season is 120 to 160 days over most of the region, but it is somewhat less than 120 days in the higher mountains and as much as 180 days in a narrow belt along the Atlantic Coast.

Sols Bruns Acides and Podzols, both commonly with fragipans, are the dominant soils of the region. Humic Gley soils, Low-Humic Gley soils, and Bog soils occupy the lowlands and depressions. Stoniness imposes serious restrictions on the use of many of the soils in this region.

The production of forage for dairy cattle is the principal land use of much of the farmland in the region. Fruit, tobacco, potatoes, and various vegetable crops are important locally where markets, climate, and soils are favorable. The steeper lands are mainly in forests, which produce significant amounts of timber. Recreational uses are probably more important for much of the forested land in this highly urbanized region.

S NORTHERN ATLANTIC SLOPE TRUCK, FRUIT, AND POULTRY REGION

This region consists of the gently to steeply sloping Northern Coastal Plain, Northern Piedmont, and Northern Appalachian Ridges and Valleys. The average annual precipitation ranges from 40 to 45 inches with only a slight maximum in midsummer. The average annual temperature is 51°F., and the freeze-free season is about 180 days.

Soils on the steep slopes are mainly Sols Bruns Acides. On the gentle slopes Red-Yellow Podzolic soils are dominant, but some soils, mainly on limestone materials, are members of the Gray-Brown Podzolic group.

Poultry and dairy farming are the leading agricultural enterprises in the region, but fruit and truck crops are also important in many places. Many farms are operated on a part-time basis by people who earn most of their living in the cities. Rural residences occupy some areas where the land is less favorable for farming. The encroachment of urban areas onto farmland is a problem throughout the region. Steep slopes are largely in forests, which are used both for timber production and for recreation.

T ATLANTIC AND GULF COAST LOWLANDS, FOREST AND TRUCK CROP REGION

This region consists of the low, nearly level parts of the Atlantic and Gulf Coastal Plains.

The annual precipitation averages 50 inches in most of the region but falls off sharply in the extreme western part. The average annual temperature is 65°F. The freeze-free season ranges from 220 days in the north to 300 or more days in the south.

Low-Humic Gley soils, Ground-Water Podzols, and Bog soils are dominant along the Atlantic and Gulf Coasts east of the Mississippi River Delta. West of the Mississippi River Delta, Grumusols and Planosols are the principal soil groups.

Most of the soils are too wet to be used as cropland without artificial drainage. Drained areas are used mainly for growing truck crops and cotton and, to some extent, for improved pastures. Sugarcane and rice are important crops in Louisiana and east Texas. Undrained areas to the east of the Mississippi River Delta remain in forest.

U FLORIDA SUBTROPICAL FRUIT, TRUCK CROP AND RANGE REGION

This region consists of the southern two-thirds of the Florida peninsula. The average annual precipitation is in excess of 50 inches throughout the region. The average annual temperature is above 70°F., and the freeze-free season ranges from 280 days in the north to 365 days in the south. A large part of the region lies south of the southern limit of annual frost.

Ground-Water Podzols, Low-Humic Gley soils, and Bog soils are the dominant soil groups on the flat lands, whereas Red-Yellow Podzolic soils and sandy Regosols are dominant on the higher, more sloping ridges. There are extensive areas of Lithosols on coral limestones in the southern part of the region.

Citrus fruits, other subtropical fruits, and winter vegetables are the major crops throughout the region, but slightly more land is in pasture than in crops. More than two-thirds of the region is in forest or other native vegetation, much of which is grazed. Beef cattle are the principal livestock, but dairying is important near the larger cities. Sugarcane is a major crop locally in the south, and its acreage has been increasing rapidly in recent years.